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Axial Waterjet (AxWJ) Model 5662: Hull Resistance and Model-Scale Powering with LDV Nozzle Design

By
Dominic S. Cusanelli and Scott A. Carpenter

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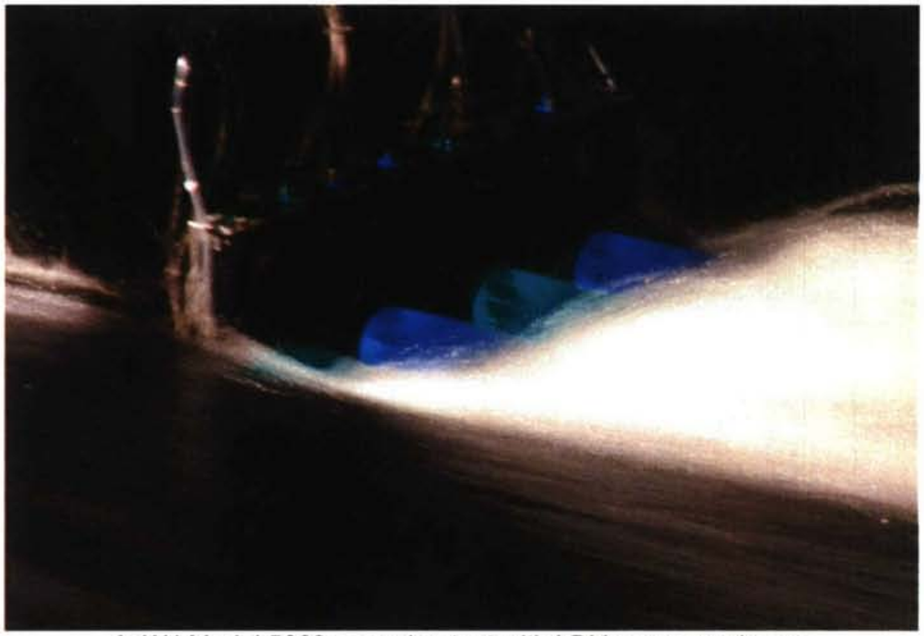

AxWJ Model 5662 powering test with LDV survey underway

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NSWCCD-50-TR-2007/059 Axial Waterjet (AxWJ) Model 5662: Hull Resistance and Model-Scale Powering with LDV Nozzle Design

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14. ABSTRACT

This report is a partial documentation of the first series of model-scale tests conducted 12/06-2/07, to evaluate the Axial Waterjet (AxWJ), Model 5662, on the Joint High Speed Sealift (JHSS) hull platform. This document contains calm water resistance and model-scale powering test results only.

Bare hull effective powers were determined for the AxWJ hull at three displacement conditions. Appended effective power was determined for the AxWJ hull with the LDV waterjet nozzles installed, at design displacement. Bare hull and appended effective powers for AxWJ were compared to those of the JHSS Baseline shaft & strut (BSS) hull.

Model scale rotor force measurements were recorded for the AxWJ under power. These tests were conducted with waterjet nozzles specifically designed for the purpose of LDV flow survey measurements. During testing, the transom flow was observed to impinge on the nozzle hardware included for LDV measurement purposes, resulting in additional hull drag and power.

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Detailed powering analysis derived from the LDV and pressure tap measurements, including full-scale powering predictions, will be reported in a separate document.

ADMINISTRATIVE INFORMATION

Funding for the evaluation of the Axial Waterjet on the JHSS hull platform was through the Office of Naval Research, "ONR Compact High Power Density Waterjet FNC Program", Project Manager Ki-Han Kim (ONR 331). The US Navy's Sealift R&D Program is managed through the Strategic & Theater Sealift Program Office PMS 385. The Joint High Speed Sealift (JHSS) Program Project Manager is William Davison (PMS 385). The JHSS Hydro Working Group (HWG), which includes representatives from NAVSEA, NSWCCD, ONR and CSC, coordinates all hydrodynamic, propulsion, hullform, and structural loads R&D for these combined programs.

Model tests were conducted at the David Taylor Model Basin, Naval Surface Warfare Center, Carderock Division Headquarters, (NSWCCD), by the Resistance & Powering Division (Code 5200) and the Propulsion and Fluid Systems Division (Code 5400), under work unit numbers 06-1-5030-105/106.

INTRODUCTION

The Joint High Speed Sealift (JHSS) was a potential FY12 ship acquisition sponsored by OPNAV N42. The program was originally designated the Rapid Strategic Lift Ship (RSLS) as outlined in "Rapid Strategic Lift Ship Feasibility Study Report" [Ref. 1]. In the "Joint High Speed Sealift (JHSS)" presentation [Ref. 2], the ship's capability was broadly described as being able to "Embark design payload, transport it 8,000 nm at 36 knots or more, and disembark it to a seabase or shore facility". Under the auspices of several Program Offices, three different types of propulsion systems are being evaluated on the JHSS hull platform: (1) conventional open propellers on shafts and struts, (2) waterjet propulsion, and (3) pod propulsion.

The entire evaluation of waterjet propulsion on the JHSS hull platform is to include the construction and testing of two model hulls, the Axial Waterjet (AxWJ) Model 5662, and the Mixed-Flow Waterjet (MxWJ) Model 5662-1. The extensive testing planned for the two waterjet models, which will extend over a period of more than eight months, as well as details pertaining to the design of the waterjets, will be summarized in a single volume after the conclusion of the test programs and analysis period. In the interim, several reports of smaller scope, documenting single series of experiments, will be prepared.

This report is the documentation of the first series of model-scale calm water resistance and powering tests, conducted 12/06-2/07, on the AxWJ Model 5662. The scope of testing within this first series is outlined in the Test Agenda, Appendix A, Table A1. This document is intended to be a record of the model test resistance and powering data with analysis presented for resistance only. Powering analysis for waterjets requires a significant scope of testing to define mass flow and pressures within the waterjet system. This subsequent testing and analysis on the AxWJ model data and full-scale predictions of waterjet powering on this hull, as well as the testing and analysis of the MxWJ, will be reported in subsequent documents.

HULL MODEL

Resistance and propulsion Model 5662, representative of the Axial Waterjet (AxWJ) propulsion variant of the JHSS hull platform, built of fiberglass to a linear scale ratio $\lambda = 34.121$, and LBP = 27.86 ft (8.5 m), was manufactured at NSWCCD. Photographs of completed Model 5662 with LDV nozzles installed are presented in Figure 1. The AxWJ Model 5662 scale ratio is equivalent to that of the JHSS Baseline Shaft & Strut (BSS) hullform Model 5653 [Ref. 3].

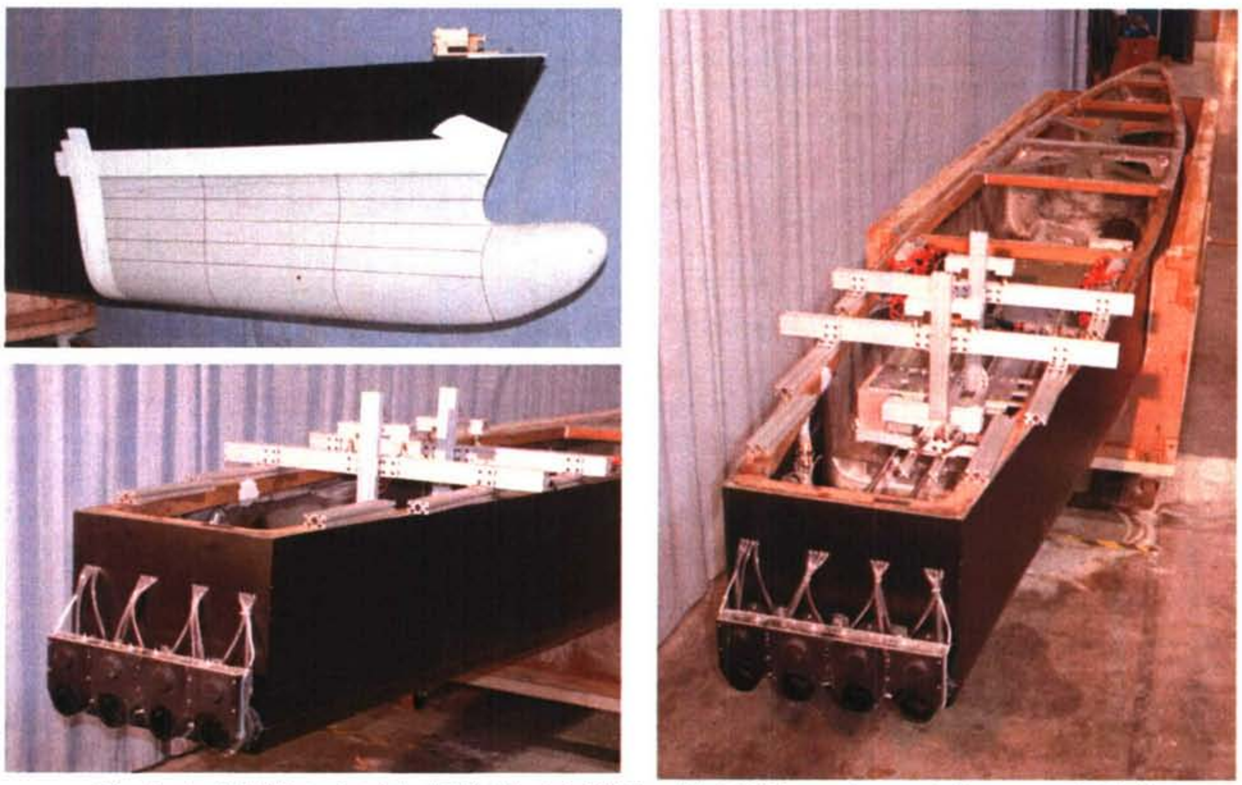

Fig 1. Axial Waterjet (AxWJ) Model 5662 with LDV nozzles and Gooseneck Bulb

Construction

The Axial Waterjet (AxWJ) Model 5662 hull is essentially comprised of two half-models, a bow half and a stern half, separable at a part-line at Station 10 amidships, allowing interchangeable stern sections to be tested: AxWJ Model 5662 and subsequent Mixed-Flow Waterjet (MxWJ) Model 5662-1. Both bow and stern sections were built using a 3/8-inch fiberglass composite hull, decking, and bulkheads to reduce weight and cost. Photographs taken throughout the construction and equipment outfitting phases of AxWJ Model 5662 are presented in Appendix B, Figure B1. Prior to and during this initial test series, AxWJ Model 5662, both bow and stern sections, were painted black.

The bow section included a cut-out (demarked by edge of black painted surface and white fairing tape) for interchangeable bow designs as well. For this test series, the Gooseneck Bulb (GB), painted grey, was installed on Model 5662, as shown in Figure 1. The GB was selected as the optimal tested bow design for the JHSS hull platform during the BSS Series 1 tests [Ref 3].

A unique feature of AxWJ stern half-model was its construction with a cut-out into which a large waterjet stern plug assembly containing the waterjets and LDV mount points was installed. The waterjet stern plug was manufactured in four sections using a stereolithography[1] apparatus (SLA) process, and joined together before being mated with the hull, Figure 2.

Integrated features of the AxWJ Model 5662 waterjet stern plug included:

- inlet and pump chamber geometry
- LDV measurement hardware mounts
- LDV window mounts
- internal pressure tap passages
- fwd impeller shaft bearing mounts
- fastener and location holes

Fig 2. Model 5662 waterjet stern plug assembly

The nozzle/stator assembly was also fabricated using the SLA process. Rather than retaining individual nozzles, the LDV nozzles were installed as a single large assembled unit that included both the waterjet nozzle components necessary for propulsion and components necessary for conducting the LDV and pressure tap measurements, Figure 3. The LDV nozzles design did not include steering or reversing buckets, which would be a necessary component of any full-scale waterjet installation.

Each nozzle included design items necessary for propulsion:

- the nozzle
- integrated stator blades and hub
- rear impeller shaft bearing mount
- water passage for bearing cooling

The LDV nozzles assembly included design items necessary for conducting the LDV and pressure tap measurements:

- external structures above the nozzles necessary to enclose the LDV water baths
- internal pressure tap passages

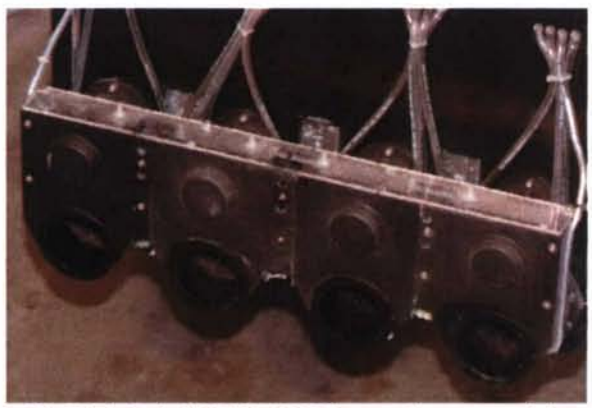

Fig 3. Model 5662 LDV nozzles assembly

The drive assembly of the model included machined composite impellers on four impeller shafts. These shafts were connected to dynamometers for the measurement of thrust and torque on each impeller shaft.

Appendage Configurations

The bare hull configuration of the AxWJ was represented on Model 5662 with the waterjet inlets (intakes) covered by thin galvanized metal plates cut to the shape of the inlets, and affixed

[1] Stereolithography is rapid manufacturing / prototyping technology additive fabrication process utilizing a vat of liquid UV-curable photopolymer resin and a UV-laser to build parts a layer at a time. On each layer, the laser traces a part cross-section pattern on the surface of the liquid resin. Exposure to the UV-laser light solidifies the pattern traced on the resin and adheres it to the layer below.

to the model with white fairing tape, as shown in Figure B2. The propulsion nozzles were not installed, and in their place was another metal plate installed flush with the vertical transom, covering the waterjet exits, again faired with white tape.

The appended resistance experiments were conducted with the LDV nozzles installed on the model, but with the waterjet inlets (intakes) remaining covered. In addition, when the inlets were opened for powering tests, right-angle ("L" shaped) pitot tubes were installed under the hull at waterjet station 1. These pitot tubes are shown in selected photographs of Figure B1.

In order to conduct Laser Doppler Velocimetry (LDV) measurements in the waterjet nozzles, which were an integral part of the initial series of experiments on the AxWJ Model 5662, a special so-named "LDV nozzle" design was employed. This nozzle design incorporated large external structures above the nozzles to enclose water baths necessary for the LDV system, as shown in Figure B3. The LDV nozzles also extended further aft, and protruded slightly outboard, of what would be expected of a propulsion-only designed nozzle. Consequently, during testing, the transom flow was observed to impinge on the LDV nozzles specific hardware, resulting in additional hull drag.

To produce turbulent flow along the model, turbulence stimulator studs of 1/8 inch diameter by 1/10 inch height, spaced 1 inch apart, were affixed to the model approximately 2 inches aft of the stem, and continuing down to and around the bulb approximately 2 inches aft of the FP.

Instrumentation for Resistance and Powering

The linear bearing, floating platform "Cusanelli" tow post [Ref. 4], was utilized for the forward attachment point of the model to the towing carriage. Mechanical connection between the tow post and model was made through a double-axis gimbal assembly. When attached through the floating platform tow post system, the model is restrained in surge, sway, and yaw, but is free to pitch, heave, and roll. The location of the model tow point was approximately ship Station 5, parallel to, and at the same level as, the design waterline (DWL). For the aft attachment point, the standard 'grasshopper' bracket was utilized, attached at approximately ship Station 15. The counter weights and vertical arm were balanced, in place, so that the arm would not impart any vertical force on the model.

Model resistance (drag) measurements were collected using a DTMB 4-inch block gauge, of 200 lbf. capacity. Model side force measurements were collected with a DTMB 4-inch block gauge, of 50 lbf. capacity. Side force is monitored at the tow post attachment point during calm water experiments in order to maintain an essentially zero side force to insure zero yaw angle. Dynamic sinkage (defined as positive downward) was measured by wire potentiometers, which were located at the intersection of the deck line at Station 6 forward and Station 15 aft.

The thrust and torque on all four rotor shafts were measured with Kempf and Remmer's (K&R) model R31 dynamometers, of 22lbf. thrust (T) / 35in-lbf. torque (Q) capacity. To insure equivalent shaft rotational speed (RPM), rotor shaft pairs, port and starboard, were driven through 1:1 drive ratio "T" gearboxes and coupled so that both shaft pairs were each powered by a single constant-torque electric drive motor. The two drive motors were electronically synchronized to maintain nominally equivalent RPM. Shaft rotation for all four rotors was inboard-over-the-top. A 60 tooth wheel and magnetic pickup / pulse counter system was used to determine shaft RPM, for each shaft pair.

Calibration of all aforementioned instrumentation was performed prior to the tests in the NSWCCD Code 5200 calibration lab by D. Mullinix (CSC contractor).

Displacement, Trim, and Wetted Surface

AxWJ bare hull resistance tests were conducted at the three JHSS hullform displacement conditions, the design displacement (DES) of 36,491 tons, a light displacement (LITE) of 32,841 tons representing a 10 percent reduction in displacement from design, and a heavy displacement

(HVY) of 40,140 tons representing a 10 percent increase in displacement from design. All conditions were ballasted at static even keel (zero trim). Appended resistance and powering tests were conducted at only the DES displacement.

Hull hydrostatic calculations were made for the AxWJ bare hull, at each displacement condition, using the Code 5200 proprietary program "Hydro". However, unbeknownst to the authors, prior to the test series two different electronic hull surface geometry files had been circulated. The first surface file, from which Model 5662 had been constructed, did not contain a centerline skeg. The second file, from which all of the pre-test hydrostatic calculations were derived, included a centerline skeg. This discrepancy was not discovered until well after the completion of this and the subsequent three waterjet test series. Therefore, incorrect values of wetted surfaces (higher values, with skeg) were calculated and utilized throughout the model test series. Post-test, hull hydrostatic calculations were determined with the correct model configuration, as tested, without centerline skeg. Presented in Table A2 are the hull hydrostatic calculations for the AxWJ at design displacement (DES), and the ship/model test parameters for each displacement, corresponding to the model configuration without a centerline skeg, as tested.

Adjustments were made in the post-test re-analysis of the AxWJ Model 5662 data to account for these changes in wetted surfaces. Table 1 presents the ship hydrostatic values, in brief, utilized for the analysis presented herein, corresponding to the correct model configuration, as tested, without centerline skeg.

Table 1. AxWJ ship hydrostatics, in brief, utilized herein

AxWJ	Design (DES)	Heavy (HVY)	Light (LITE)
DISPLACEMENT (tons)	36491	40140	32841
LWL (ft)	979.4	948.5	981.6
WETTED SURFACE (ft^2)	96696	100380	92896
DRAFT (ft)	28.3	30.1	26.5

MODEL TEST RESULTS

Resistance and powering test data and analysis for the Axial Waterjet (AxWJ) Model 5662 are presented in Appendix A. The ship-model correlation allowance of $C_A = 0.0$ was recommended by NSWCCD Code 5200 based on the NAVSEA guidance as modified by more recent correlation allowance experience. The value of $C_A = 0.0$ was agreed upon by the JHSS Hull Working Group (HWG). Effective power predictions are made for the full-scale AxWJ operating in smooth, deep, salt water, with a uniform standard temperature of 59°F.

Bare Hull Resistance

Bare hull resistance experiments were conducted on AxWJ Model 5662, at the three displacements, DES, HVY, and LITE. Tests were conducted across the speed range of 15 to 45 knots. Again, bare hull was represented with the waterjet inlets (intakes) and waterjet outlets covered by metal plates, and the LDV nozzles were not installed. The bare hull effective power (PE) predictions for the full-scale AxWJ, at three displacements, are presented and compared in Figure A1 and Tables A3-A6, and summarized at selected speeds in Table 2. The presented bare hull PE predictions have been adjusted to reflect the correct hull hydrostatics (Table 1) corresponding to the hull configuration without a centerline skeg. For the AxWJ, relative to the DES displacement, the 10% increase in displacement (HVY) resulted in a 10.4% average increase in resistance across the speed range, and conversely, the 10% reduction in displacement (LITE) resulted in an average 9.9% reduction in resistance.

Table 2. AxWJ bare hull effective powers, selected speeds

	Design (DES)	Heavy (HVY)		Light (LITE)	
VS (knots)	PE (hp)	PE (hp)	Δ PE (%)	PE (hp)	Δ PE (%)
25	29492	33237	+12.7%	25511	-13.5%
36	85242	95107	+11.6%	76820	-9.9%
39	127665	143358	+12.3%	115258	-9.7%

A comparison of the AxWJ predicted bare hull PE at DES displacement to that of the pre-test estimated PE[2], over the speed range of 15 to 40 knots, is presented in Figure A2 and Table A6. The AxWJ data shows a PE varying within ± 4% that of the pre-test estimate over the speed range of 15 to 35 knots. At speeds of 36 knots and above, the model test predicted PE begins to diverge from the pre-test estimate, constantly exhibiting a higher value. Across the speed range, the model test PE prediction averages 1.4% higher than that of the pre-test estimate.

Appended Resistance - LDV Nozzle Design Implications

The LDV nozzles assembly had large vertical surfaces to house the water bath, and extended further aft and protruded slightly further outboard, than what would be expected of propulsion-only designed nozzles. Consequently, during testing, the transom flow was observed to impinge on the LDV nozzles specific hardware. This flow impingement would result in additional hull drag greater than that associated with standard propulsion-only designed nozzles. In order to determine the added resistance due to the LDV nozzle design, the following resistance condition was examined. The LDV nozzles assembly was installed while the waterjet inlets (intakes) remained covered. This resistance evaluation was conducted at only the seven powering test speeds (i.e. 15, 20, 25, 30, 36, 39, and 42 knots). The appended PE of the AxWJ with the LDV nozzles installed was compared to the bare hull PE, and is presented in Figure A3 and Table A7. The appended PE prediction is adjusted to reflect the correct hull hydrostatics. Averaged across the seven tested speeds, in the range of 15 to 42 knots, the AxWJ with the LDV nozzles installed exhibited a PE of 3.0% higher than that of the bare hull. The largest increase was measured at 30 knots, where the LDV nozzles increased the PE by 4.9%.

Model-Scale Rotor Forces: Ship Propulsion Point, As Tested

The Model 5662 powering experiments were conducted at seven powering test speeds of 15, 20, 25, 30, 36, 39, and 42 knots (equivalent full-scale). Photographs of Model 5662 during the powering tests, both with and without the LDV system operating (speeds unrecorded), are presented in Figure B4. The AxWJ Model 5662 powering test rotor force measurements, as tested, are presented in Figure A4 and Table A8.

Model-scale rotor RPM and force measurements of thrust and torque were recorded, after the model attained a steady state sinkage and trim, and rotor RPM was adjusted manually to attain the calculated model drag force (F_D) to emulate the ship propulsion point. F_D was calculated according to the traditional formula, using the ITTC ship and model friction coefficients, correlation allowance, wetted surface corresponding to the bare hull condition, and no form factor. Due to the aforementioned discrepancy in the pre-test calculations of hull wetted surface, the values of F_D to which the model was adjusted during this series of testing were biased high.

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[2] The AxWJ bare hull resistance pre-test estimate was prepared by Fung (Code 2420), based on proprietary speed-independent regression equations, where residuary resistance coefficients were a function of the ship's hull form parameters, (i.e. displacement-length ratio, beam-draft ratio, prismatic coefficient, maximum section area coefficient, half-entrance angle, bow bulb transverse section area/vertical location, and transom configuration). The pre-test estimate was then modified by Cusanelli to reflect the resistance effect of the Gooseneck Bulb.

Values presented in Figure A4 and Table A8 represent the model-scale forces as measured at the incorrect F_D value. Subsequent analysis to adjust the model propulsion and rotor forces to reflect the correct values of F_D will also be presented within this document.

Model-Scale Rotor Forces: Over and Under-Propulsion

Model-scale powering data for the AxWJ Model 5662 was collected for over and under-propelled conditions, at equivalent ship speeds of 25 and 36 knots. The model rotor RPM was adjusted to nominal $\pm 5\%$ and $\pm 10\%$ of the values determined for the ship propulsion point as presented above. Rotor RPM increases above the value at ship propulsion point is defined as over-propelled (reduced F_D), and conversely, RPM below ship propulsion point is defined as under-propelled (increased F_D). The model rotor force measurements for AxWJ Model 5662, in the over- and under-propelled conditions, are presented in Figure A5 and Table A9.

Included in Table A9 is a comparison of the interpolated propulsion point (at the tested values of F_D) from over/under propulsion test to that determined from standard powering test technique. A time span of two weeks separated the standard powering test and the over/under propulsion test. The determined values of rotor RPM to attain 25 and 36 knots differed by less that 1% between the two test techniques. While the individual rotor forces appeared to vary somewhat, the total values of thrusts and torques for all four rotors, at 25 knots differed by 1.3% an 1.1% respectively, and at 36 knots differed by only 0.5% and 0.1% respectively. It can it be concluded that over/under propulsion test did not necessarily add any more accuracy to the measured forces at the ship propulsion point, as tested.

The collected data from the over/under propulsion test has proved to be invaluable, as it was used post-test to re-analyze the powering data at the corrected F_D values due to the wetted surface discrepancy. Tabulated values of rotor forces for varying F_D values were derived from the over/under propulsion test at ship speeds of 25 and 36 knots only. Estimates were made of rotor forces for varying F_D values at the additional 5 powering test speeds, 15, 20, 30, 39, and 42 knots, using the measured values for each speed at the tested F_D, and adjusting these values based on the individual slopes of the curve fits to the over/under powering data measured at 25 and 36 knots. The estimated over/under propulsion forces, at the additional 5 powering test speeds, are presented in Table A10.

Model-Scale Rotor Forces: Estimated At Corrected Ship Propulsion Point

The AxWJ Model 5662 powering test rotor force measurements, estimated at the corrected ship propulsion point (correct F_D values) by utilizing the over/under propulsion test data, for each of the seven powering test speeds, are presented in Figure A6 and Table A11. At all test speeds, the value of F_D was reduced by 6.5% due to the reduction in calculated ship wetted surface, necessitating an increase in rotor RPM and an associated increase in thrust and torque on all shafts, in order to attain the corrected ship propulsion point.

For comparison, included in Table A11 are the rotor force measurements estimated from the over/under propulsion test data, at the original propulsion point (incorrect F_D) as tested. On average across the seven test speeds, the reduction in F_D of 6.5% necessitated an increase in model rotor RPM of 1.3%, and increases in model rotor thrust and torque of 2.8% and 2.9%, respectively.

The rotor force measurements determined during model-scale powering tests are reflective of the model scale pump efficiencies. Direct extrapolation of these rotor forces will not be representative of the expected power requirements of the full-scale waterjets. Full-scale pump efficiencies have been determined to be significantly higher than those measured at model scale. Powering analysis for waterjets requires a significant scope of additional testing and analysis to define mass flow and pressures within the waterjet system. This subsequent testing on the

AxWJ, continued analysis, and full-scale predictions of waterjet powering on this hull, will be reported in subsequent documents.

Model Test Uncertainties - Resistance & Rotor Force Measurements

AxWJ Model 5662 measurement uncertainties were determined for the quantities of model speed, hull resistance, and for combined inboard and outboard shafts quantities of shaft thrust, torque, and rotational speed (RPM). Overall uncertainties were determined by combining bias and precision limits using the root-sum-square (RSS) method for a 95 percent confidence level. The values for torque and RPM were then used to determine the uncertainty in the calculation of delivered power. Model 5662 resistance and powering measurement uncertainties are presented in Table A12.

Resistance measurement uncertainties, at 25 and 36 knots, were determined to be $\pm$0.46% and $\pm$0.35% of the measured nominal mean values, respectively. Likewise, the model scale delivered power measurement uncertainties were $\pm$2.13% and $\pm$1.59%, at 25 and 36 knots. The stated uncertainties for measured model delivered power reflect the combined measurement uncertainties of eight model quantities, shaft torque and RPM, for each of four shafts.

Dynamic Sinkage and Pitch

The dynamic sinkage and pitch of the model was recorded for each tested ship speed, during all of the resistance and powering tests. The dynamic sinkage and pitch of the AxWJ Model 5662, for all three displacements, recorded during the bare hull resistance tests (unpowered), are presented and compared in Figure A7 and Table A13. The dynamic sinkage and pitch recorded during the powering tests at DES displacement are presented, and compared to the values from the DES bare hull test, in Figure A8 and Table A14.

The waterjet propulsion does exhibit some measurable effects on the running trim of the model. Presumably due to the suction force of the operating waterjets on the AxWJ Model 5662, the measured dynamic sinkage and pitch was significantly different during the powering tests as compared to the bare hull resistance tests. Across the entire tested speed range, 15 to 42 knots, the recorded sinkage at the Aft Perpendicular (AP) was greater when the waterjets were operational. Consequently, the sinkage at the Forward Perpendicular (FP) was reduced.

ROM ESTIMATE OF AxWJ FULL-SCALE POWERING

Direct extrapolation of model-scale rotor force measurements will not be representative of the expected power requirements of the full-scale waterjets, due to significant differences in model vs. full-scale pump efficiencies. In addition, the present tests were conducted on a model configuration without the installation of a centerline skeg. It is the opinion of the HWG that the full-scale AxWJ would likely require a centerline skeg for structural support during construction and dry-docking, and for directional stability.

For a preliminary evaluation of AxWJ powering performance, a rough order of magnitude (ROM) estimate of full-scale powering expected from the full-scale AxWJ was prepared. This ROM powering estimate utilized estimated full-scale appended effective power, and the accepted range of waterjet propulsion coefficients (PC_{WJ}).

In order to estimate the AxWJ appended resistance with a centerline skeg, an estimate of the added effective power due to the installation of a centerline skeg on the AxWJ was prepared by H. Liu (Code 5200), based upon his previous appendage drag evaluation.[3] The skeg design utilized was that previously included on the AxWJ hull. This skeg increases the hull wetted surface by 6667ft^2 (6.5% increase). The skeg added effective power was applied to the resistance prediction for the AxWJ with LDV Nozzles.

[3] NSWCCD report of limited distribution

The propulsive coefficient for waterjet propulsion, relating the 'appended' hull resistance to required propulsion power, when at speeds in the upper portion of the JHSS hull platform range (30 to 42 knots), has an accepted value in the range of $0.65 \leq PC_{WJ} \leq 0.68$. For speeds below 30 knots, trends in the PC_{WJ} show that it can reduce significantly in value. A recent waterjet evaluation program, conducted by the US Navy on the X-Craft at a range of loadings, included both model-scale and full-scale powering experiments at low speeds. Ship/model powering correlations were determined by Metcalf[4] (Code 5200) from which can be determined a range of PC_{WJ} for ship speeds below 30 knots. Coincidentally, the range of values for PC_{WJ} determined from the X-Craft study, averaged over the speed range of 30 to 42 knots, is 0.64 to 0.68. The aforementioned values for PC_{WJ} were derived primarily from mixed-flow pumps, as used in most current commercially available waterjets, and therefore, may not reflect full-scale performances of axial pump waterjets.

Applying the range of accepted PC_{WJ} at speeds of 30 knots and above, and the range in PC_{WJ} from the X-Craft evaluation to speeds below 30 knots, to the appended AxWJ (with LDV nozzles and centerline skeg), at design displacement, yields the preliminary rough order of magnitude (ROM) powering estimate for the AxWJ, as presented in Table 3.

Table 3. AxWJ preliminary rough order of magnitude (ROM) powering estimate

	AxWJ Appended*	AxWJ Preliminary Rough Order of Magnitude (ROM) Powering Estimate					
Vs (kts)	PE (hp)	Range of PC_{WJ}			Range of PD (hp)		
15	7088	0.46	-	0.53	15566	-	13410
20	16383	0.54	-	0.57	30580	-	28740
25	32477	0.58	-	0.61	56134	-	53224
30	52839	0.65	-	0.68	81290	-	77704
36	93640				144062	-	137706
39	140776				216579	-	207024
42	208906				321394	-	307215

*LDV Nozzles PE prediction plus Centerline Skeg Added PE Estimate

The Table 3 preliminary rough order of magnitude (ROM) powering estimate is for preliminary evaluation purposes only. Full-scale predictions of waterjet powering on the AxWJ hull will be reported, in a subsequent document, after the completion of additional testing and analysis to define mass flow and pressures within the waterjet system.

COMPARISONS BETWEEN AxWJ AND JHSS BASELINE BSS

A comparison of the AxWJ bare hull PE, at the three displacements, to that of the bare hull JHSS baseline shafts & struts (BSS) parent hullform, is presented in Figure A9 and included in Table A6. The AxWJ at DES, HVY, and LITE displacements, respectively, exhibited a speed-averaged bare hull resistance of 16.4%, 16.6%, and 10.2% higher than that of the bare hull BSS at equivalent displacement. Increase in bare hull resistance for the AxWJ over that of the BSS is likely a result of the greater volume and depth of transom in the AxWJ design. The AxWJ transom depth was dictated primarily by the criteria, that, in order to assure rotor priming, half of the waterjet inlet diameter should remain submerged at design displacement.

The appended PE of the AxWJ, with LDV nozzles installed, was compared to that of the JHSS baseline shafts & struts (BSS) hull, fully appended (shafts & struts, rudders, and stern flap), at DES displacement, and is presented in Figure A10 and included in Table A7. Averaged across the seven tested speeds, in the range of 15 to 42 knots, the AxWJ with the LDV nozzles

[4] Upcoming NSWCCD report

installed exhibited a PE of 8.2% lower than that of the fully appended BSS hull. This comparison indicates that even though the AxWJ bare hull exhibits increased resistance due to its increased transom volume, when compared to that of the baseline BSS bare hull, the requirement of additional appendages on the BSS hull for propulsion (i.e. shafts & struts, rudders) increases that hull's appended resistance to a value greater than the AxWJ hull (which requires only the waterjet nozzles and no corresponding shaftline appendages or rudders). Two additional facts should be noted, however: (1) The LDV nozzles design did not include steering or reversing buckets, which would be a necessary component of any full-scale waterjet installation. It is unknown whether such components, which could be designed so as to retract, would have any influence on resistance. (2) The LDV nozzles design did impinge on the transom flow resulting in additional hull drag greater than that expected for standard propulsion-only designed nozzles.

A direct comparison between a full-scale powering prediction for the AxWJ and that of the JHSS baseline BSS cannot be presented as of this writing. Unlike the open propeller shaft and strut BSS Model 5653 data, the model-scale data from the waterjet propelled AxWJ cannot be directly extrapolated to full-scale powering values. The rotor force measurements determined during model-scale waterjet powering tests are reflective of the model scale pump efficiencies. Direct extrapolation of these rotor forces will not be representative of the expected power requirements of the full-scale waterjets, which have been shown to have significantly higher pump efficiencies. For documentation purposes only, a model-scale powering comparison between AxWJ Model 5662 and BSS Model 5653 is presented in Table A15. This comparison is strictly drawn on model-scale measured forces only, and does not reflect the expected full-scale powering results.

A comparison of the AxWJ preliminary rough order of magnitude (ROM) powering estimate, to the powering prediction for the JHSS BSS, Cusanelli and Cheskakas [Ref 5], is presented in Table 4. At high speeds of 30 knots and above, the waterjet propulsion system of the AxWJ appears to have an advantage in ship powering over that of the open propeller BSS hull. At the 39 knot speed of interest, the AxWJ has an estimated power approximately 2.5% lower than that of the BSS. For speeds below 30 knots, the AxWJ has an estimated required power significantly higher than that of the BSS.

Table 4. Comparison between AxWJ preliminary rough order of magnitude (ROM) powering estimate and JHSS baseline BSS powering prediction

	BSS Powering Prediction	AxWJ Rough Order of Magnitude (ROM) Powering Estimate	
Vs (kts)	PD (hp)	Avg PD (hp)	Δ PD (%)
15	12031	14488	+20.4%
20	26253	29660	+13.0%
25	50426	54679	+8.4%
30	83951	79497	-5.3%
36	149593	140884	-5.8%
39	217339	211801	-2.5%
42	317161	314304	-0.9%

Again, the AxWJ preliminary rough order of magnitude (ROM) powering estimate presented in Table 4 is for preliminary evaluation purposes only.

CONTINUATION OF WORK

A significant scope of this initial test series on AxWJ Model 5662 was dedicated to the waterjet flow surveys conducted with the Laser Doppler Velocimetry (LDV) system, under the direction of D. Fry (Code 5400), and to the measurement of pressures within the waterjet system, under the direction of M. Donnelly (Code 5400). Detailed explanations of both the LDV and the pressure measurement systems, recorded data, subsequent analysis, and ultimately full-scale predictions of waterjet powering on this hull, will be reported in subsequent documentation.

CONCLUSIONS

This report is the documentation of the first series of model-scale calm water resistance and powering tests, conducted 12/06-2/07, on the AxWJ Model 5662 with LDV nozzle design, a waterjet propelled variant of the JHSS hull platform. It is intended to be a record of the model test resistance and powering data and analysis, with full-scale predictions presented for resistance only.

Bare hull effective powers were determined for the AxWJ at the three JHSS hullform displacement conditions, design (DES) and $\pm$ 10% displacements. The AxWJ exhibited a nearly linear relationship between displacement variations and changes in resistance.

The AxWJ bare hull effective power was also compared to that of the JHSS Baseline shaft & strut (BSS). Increase in bare hull resistance for the AxWJ over that of the BSS is likely a result of the greater volume and depth of transom in the AxWJ design. The AxWJ transom depth was dictated primarily by the criteria, that, in order to assure rotor priming, half of the waterjet inlet diameter should remain submerged at design displacement. A relaxation in this waterjet transom depth criteria would likely reduce the resistance of the AxWJ hull.

Appended effective power was determined for the AxWJ hull with the LDV design waterjet nozzles installed. During testing, the transom flow was observed to impinge on the LDV nozzles hardware, resulting in an increase in resistance larger than that anticipated for standard propulsion-only designed nozzles.

The AxWJ with the LDV nozzles installed exhibited effective lower than that of the fully appended BSS hull. This comparison indicates that even though the AxWJ bare hull exhibits increased resistance due to its increased transom volume, when compared to that of the BSS bare hull, the requirement of additional appendages on the BSS hull for propulsion (i.e. shafts, struts, rudders) increases that hull's appended resistance to a value greater than the AxWJ hull with nozzles installed (which requires no corresponding appendages).

Model-scale rotor force measurements were recorded for the AxWJ when under power. Due to significant differences in model-scale versus full-scale pump efficiencies, direct extrapolation of rotor forces measured at model-scale will not be representative of the expected power requirements of the full-scale waterjets. Powering analysis for waterjets requires a significant scope of additional testing to define mass flow and pressures within the waterjet system. This subsequent testing on the AxWJ, continued analysis, and full-scale predictions of waterjet powering, will be reported in subsequent documents.

For a preliminary evaluation of AxWJ powering performance, a rough order of magnitude (ROM) estimate of full-scale powering expected from the AxWJ was prepared. This ROM powering estimate utilized estimated full-scale appended effective power, and the accepted range of waterjet propulsion coefficients (PC_{WJ}). The AxWJ preliminary rough order of magnitude (ROM) powering estimate is for preliminary evaluation purposes only.

A comparison of the AxWJ preliminary rough order of magnitude (ROM) powering estimate, to the powering prediction for the JHSS BSS, shows that at high speeds of 30 knots and above, the waterjet propulsion system of the AxWJ appears to have an advantage in ship powering over that of the open propeller BSS hull. For speeds below 30 knots, the AxWJ has an estimated required power significantly higher than that of the BSS.

Presumably due to the suction force of the operating waterjets on the AxWJ Model 5662, the measured dynamic sinkage and pitch was significantly different during the powering tests as compared to the bare hull resistance tests. The sinkage at the Aft Perpendicular (AP) was greater when the waterjets were operational, and consequently, the sinkage at the Forward Perpendicular (FP) was reduced. On a ship with open propellers, such as the JHSS BSS, the dynamic sinkage and pitch exhibits little change between resistance and propulsion tests.

ACKNOWLEDGEMENTS

Technical Point of Contact for the AxWJ design is Stuart Jessup (Code 503). Points of contact for AxWJ Model 5662 testing are: Dominic S Cusanelli (Code 5200) for the resistance and powering, David Fry (Code 5400) for the LDV surveys, and Martin Donnelly (Code 5400) for the pressure measurements.

Current members of the JHSS Hydro Working Group include the following individuals from NSWCCD: Jack Offutt (Code 2120), Robert Anderson (Code 2410), Siu Fung, Colen Kennell, and George Lamb (Code 2420), Stuart Jessup (Code 503), Gabor Karafiath and Dominic Cusanelli (Code 5200), Michael Wilson, Thad Michael, and John Scherer (5400), and Edward Devine (Code 6540). Additional HWG members are: Christopher Dicks (FORNATL-UK), and Jeff Bohn, Steve Morris, and John Slager (CSC).

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APPENDIX A

AxWJ MODEL 5662 RESISTANCE & POWERING DATA

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FIGURES OF APPENDIX A

TABLES OF APPENDIX A

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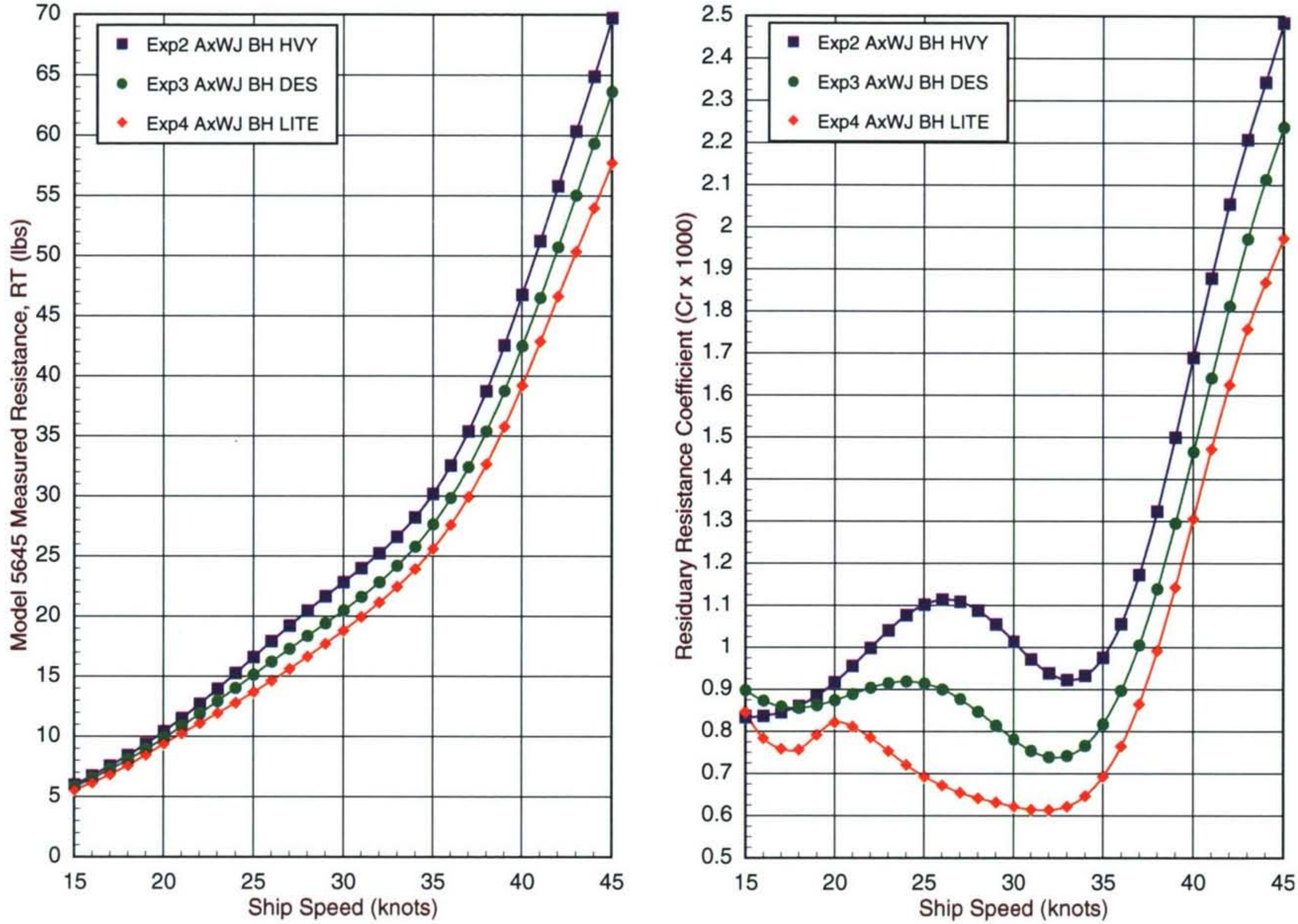


Fig A1. AxWJ BH, PE predictions, at three ship displacements

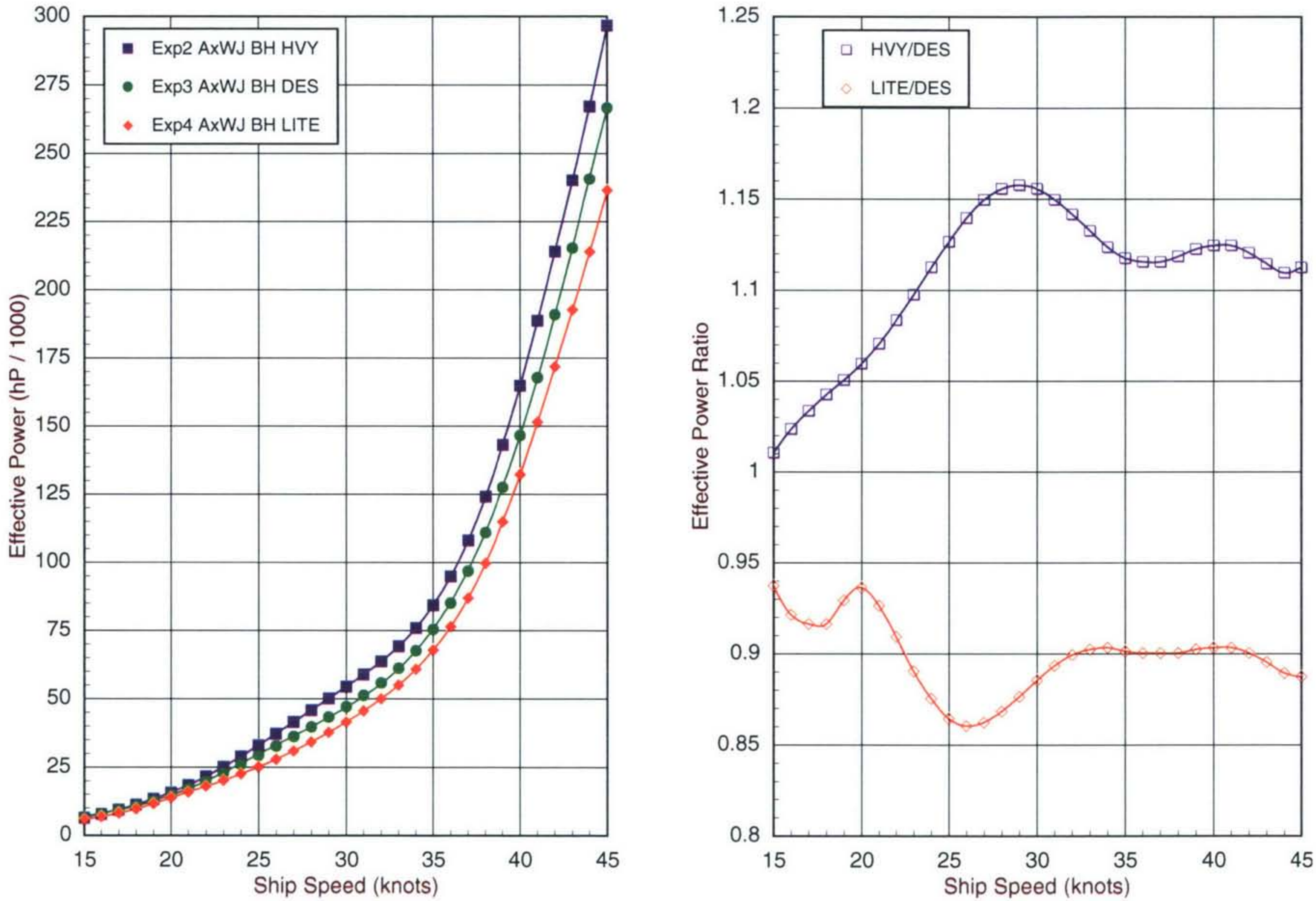


Fig A1. AxWJ BH, PE predictions, at three ship displacements (continued)

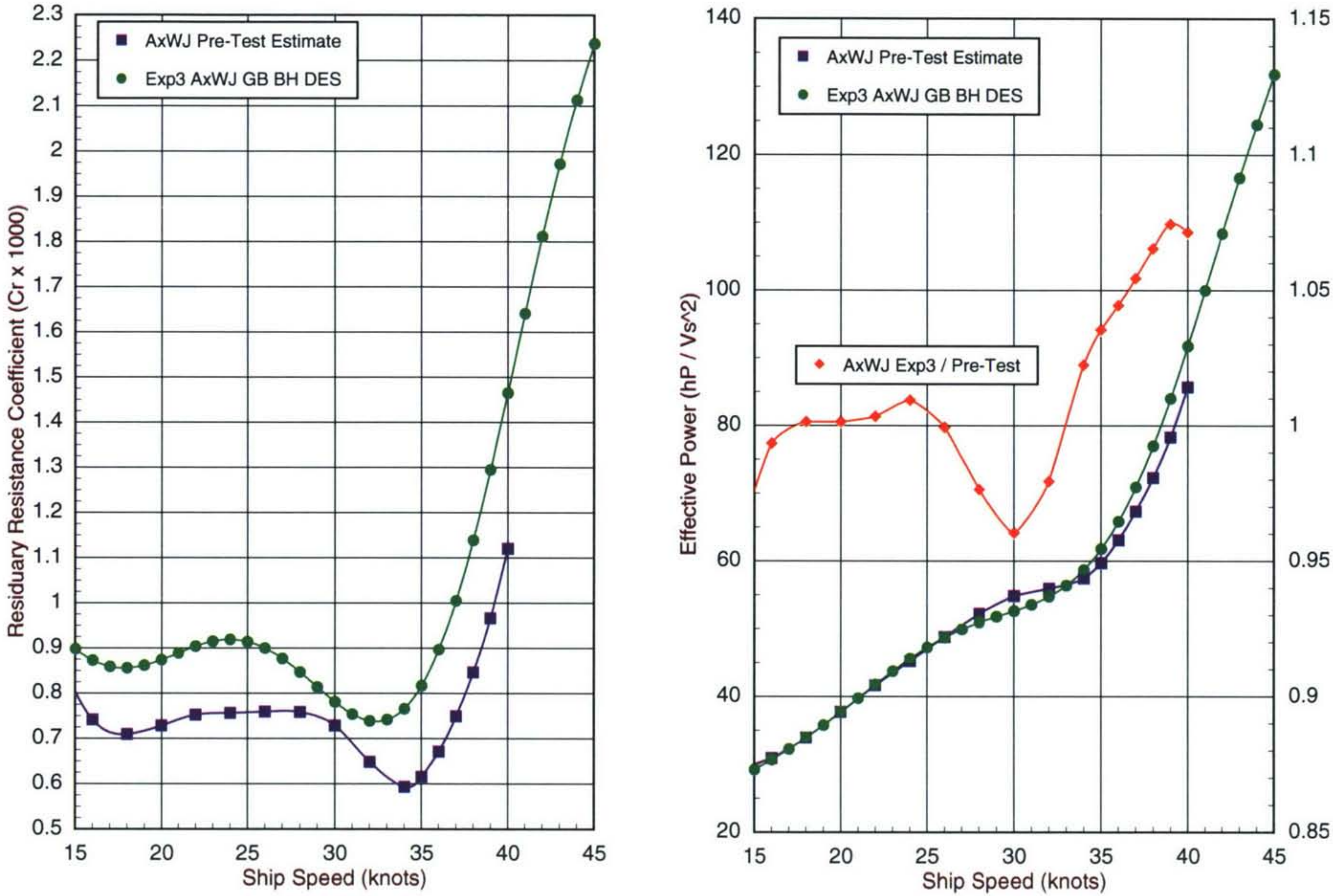


Fig A2. AxWJ BH, PE comparison vs. pre-test estimate

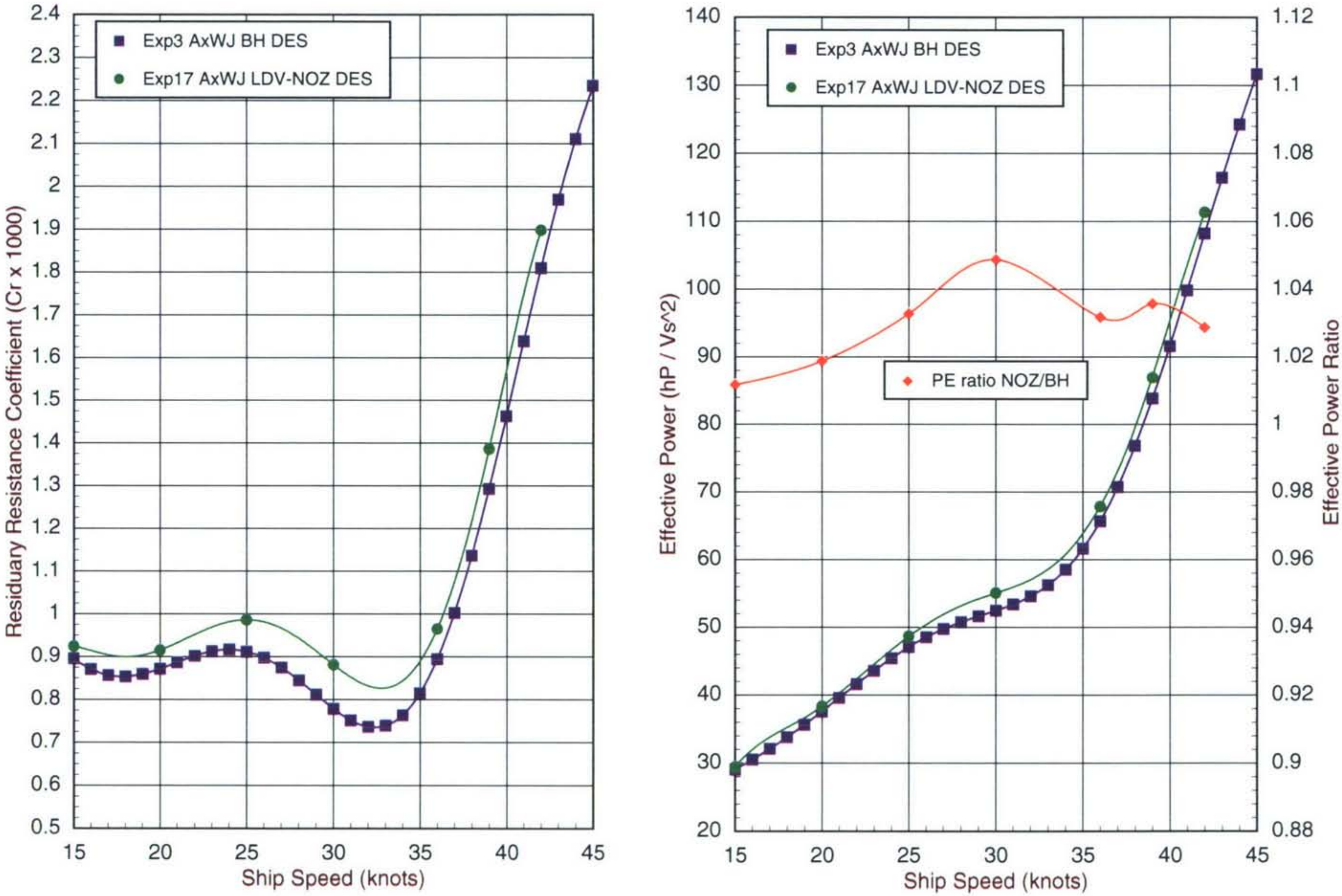


Fig A3. AxWJ, PE comparison with LDV nozzles installed (appended) vs. bare hull

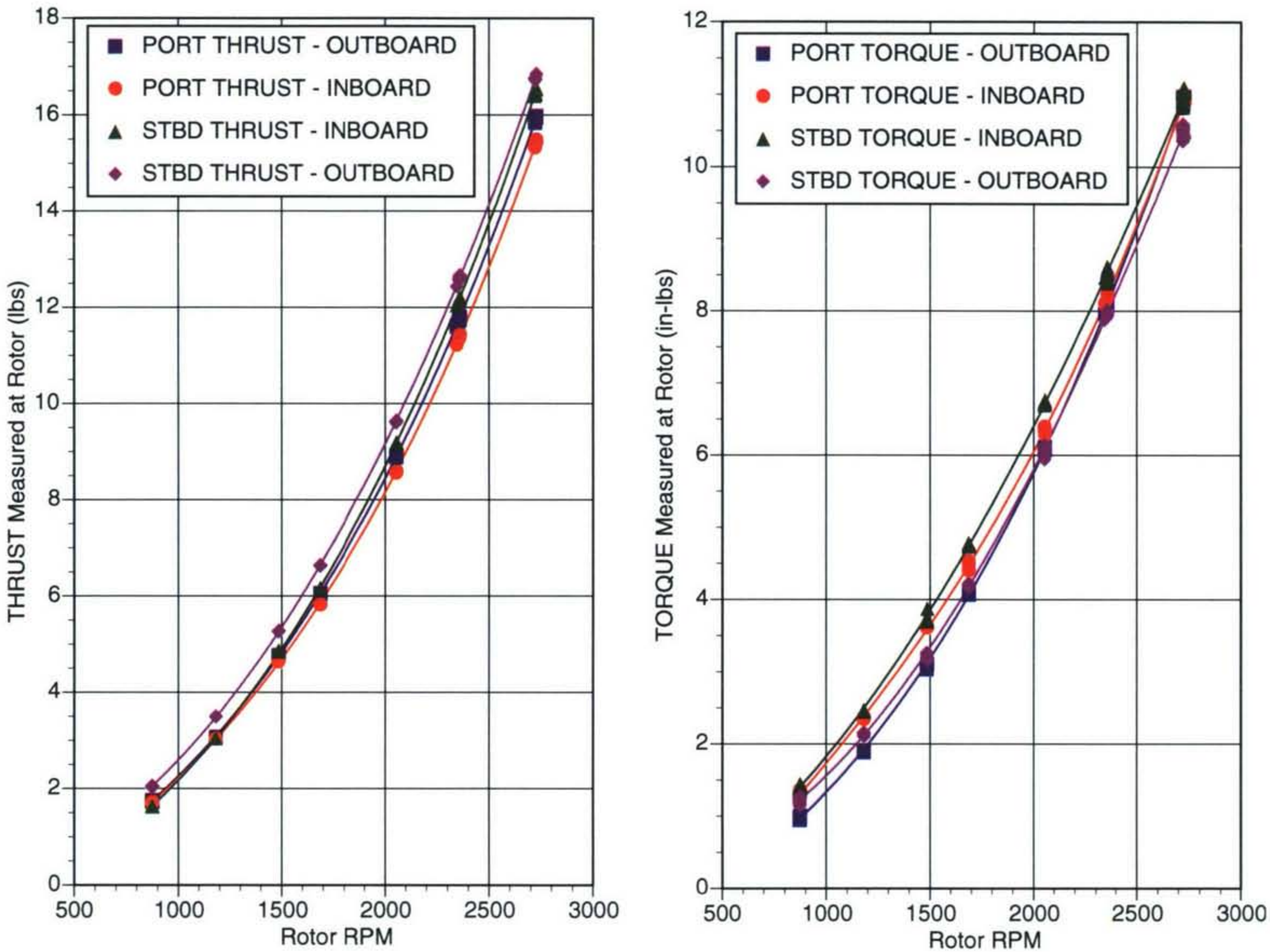
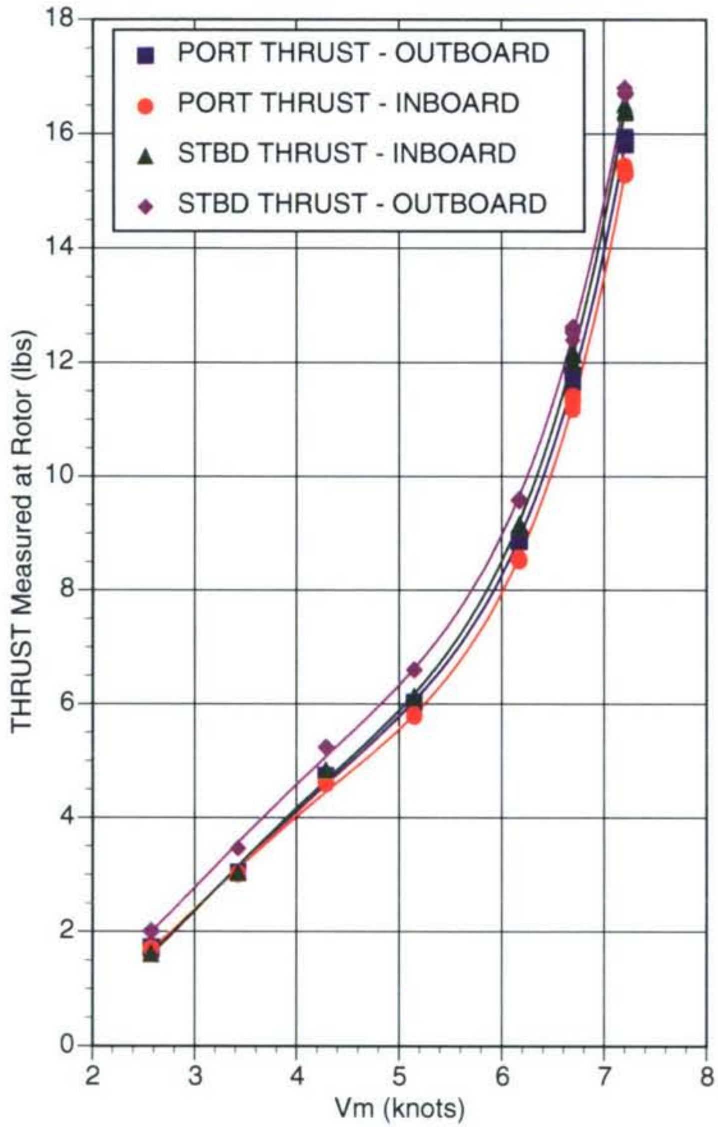


Fig A4. AxWJ powering, model-scale rotor force measurements as tested



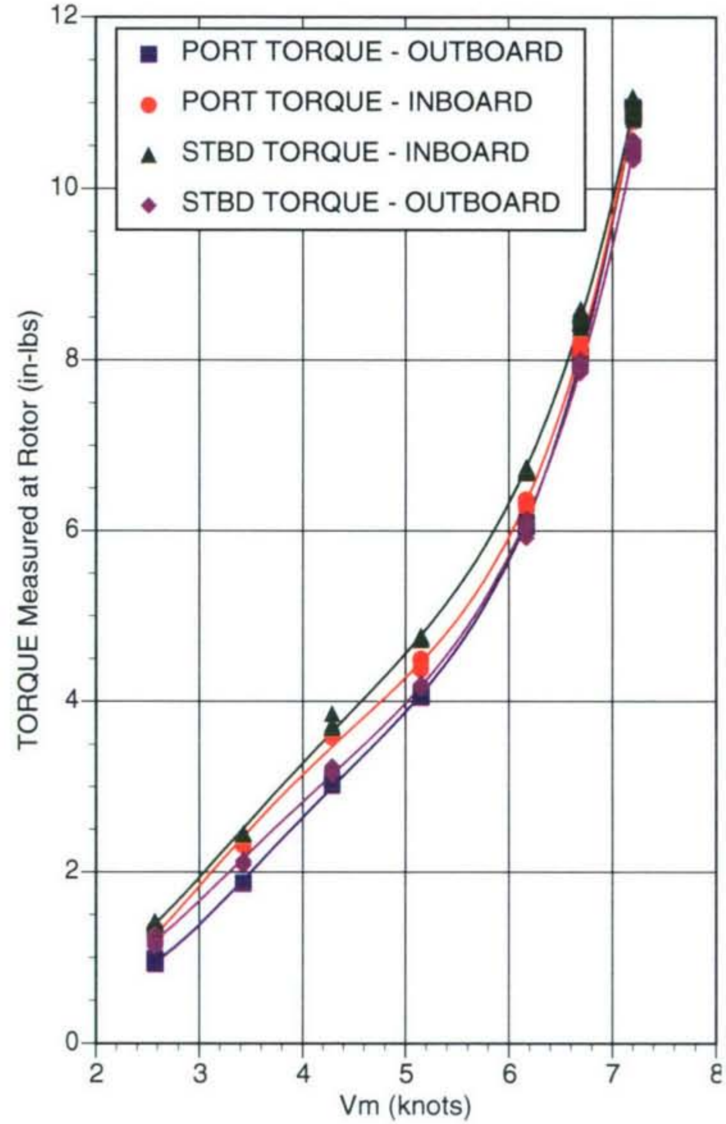


Fig A4. AxWJ powering, model-scale rotor force measurements as tested (continued)

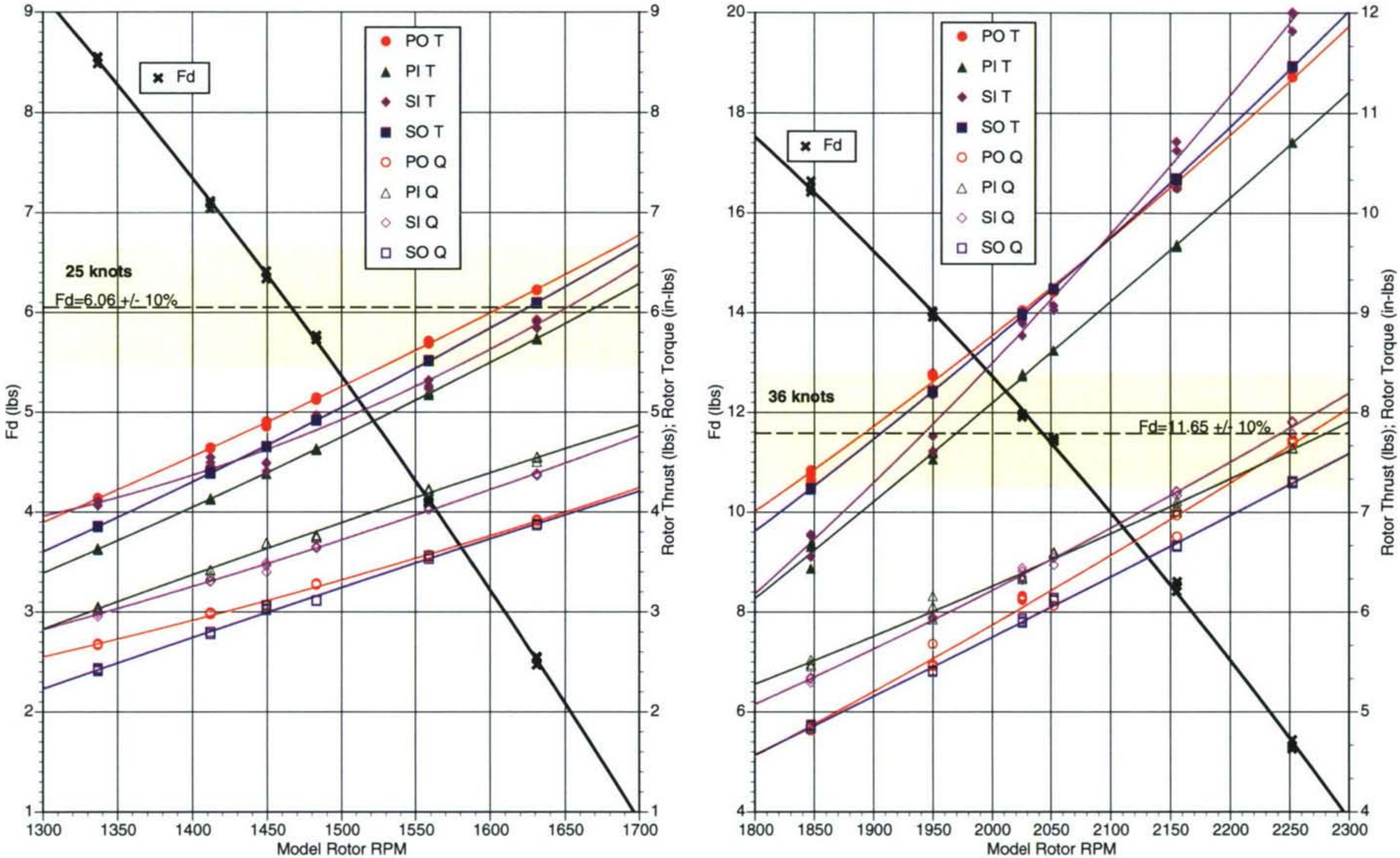


Fig A5. AxWJ, over- and under-propelled powering model-scale data, 25 and 36 knots, as tested

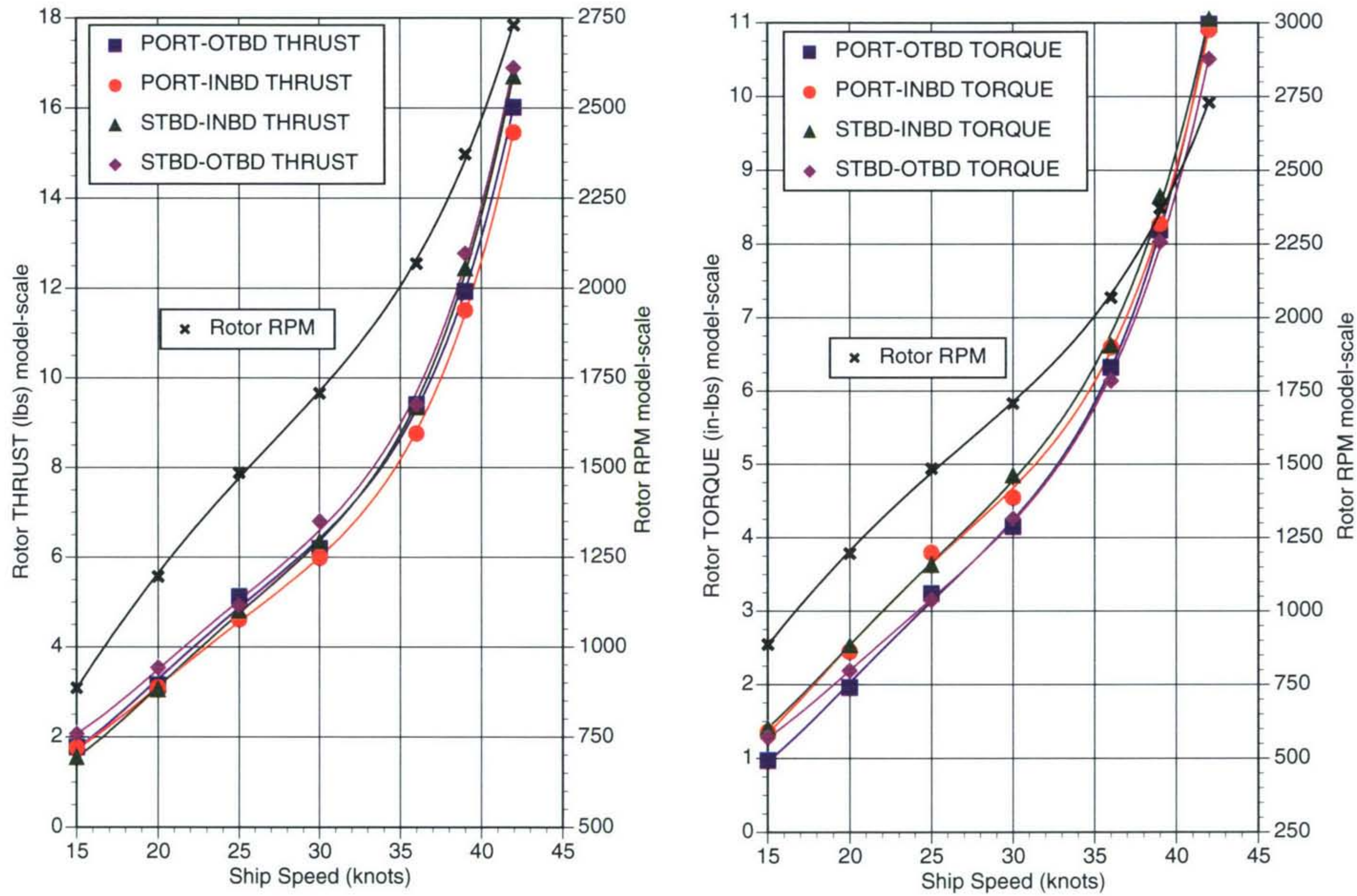


Fig A6. AxWJ powering, model-scale rotor forces at corrected ship propulsion point

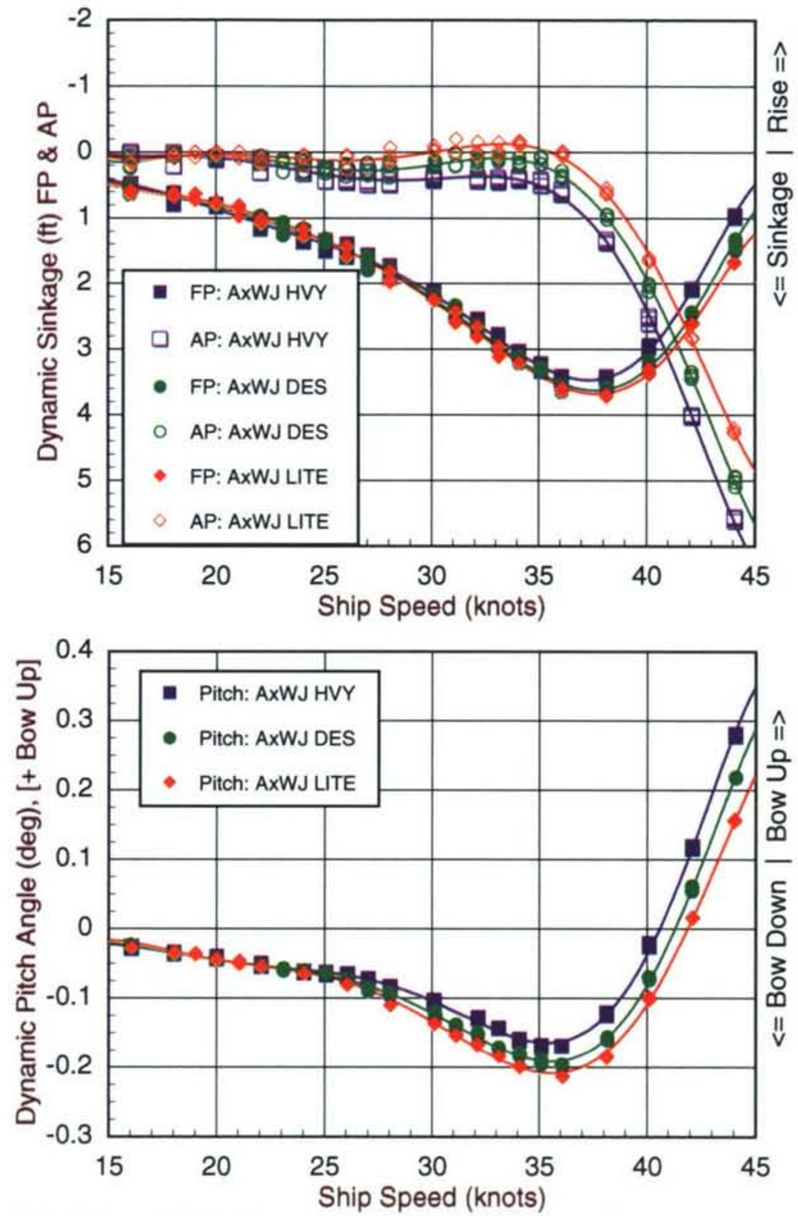


Fig A7. AxWJ BH (unpowered), dynamic sinkage and pitch, at three ship displacements

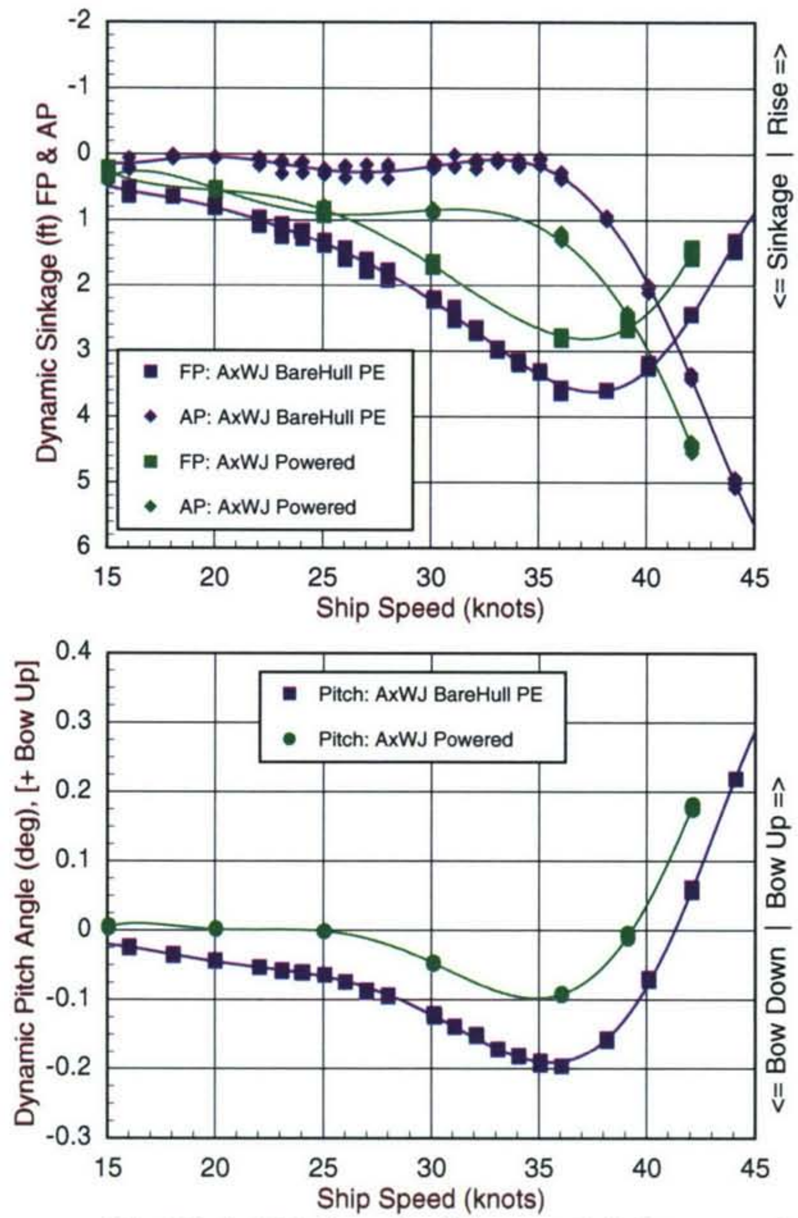


Fig A8. AxWJ, dynamic sinkage and pitch, powered vs. unpowered

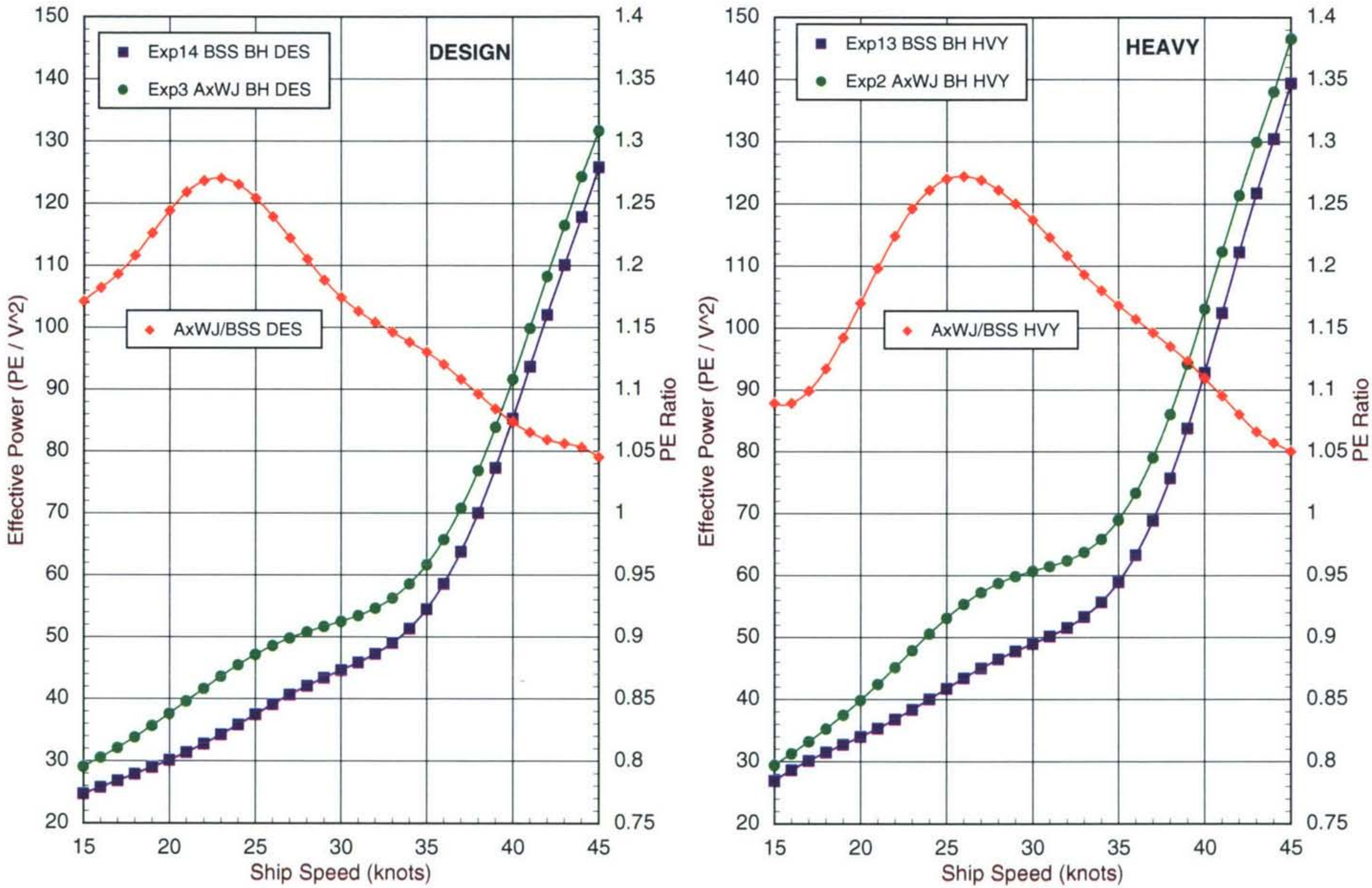


Fig A9. Bare hull PE comparisons between AxWJ and JHSS baseline BSS, three displacements

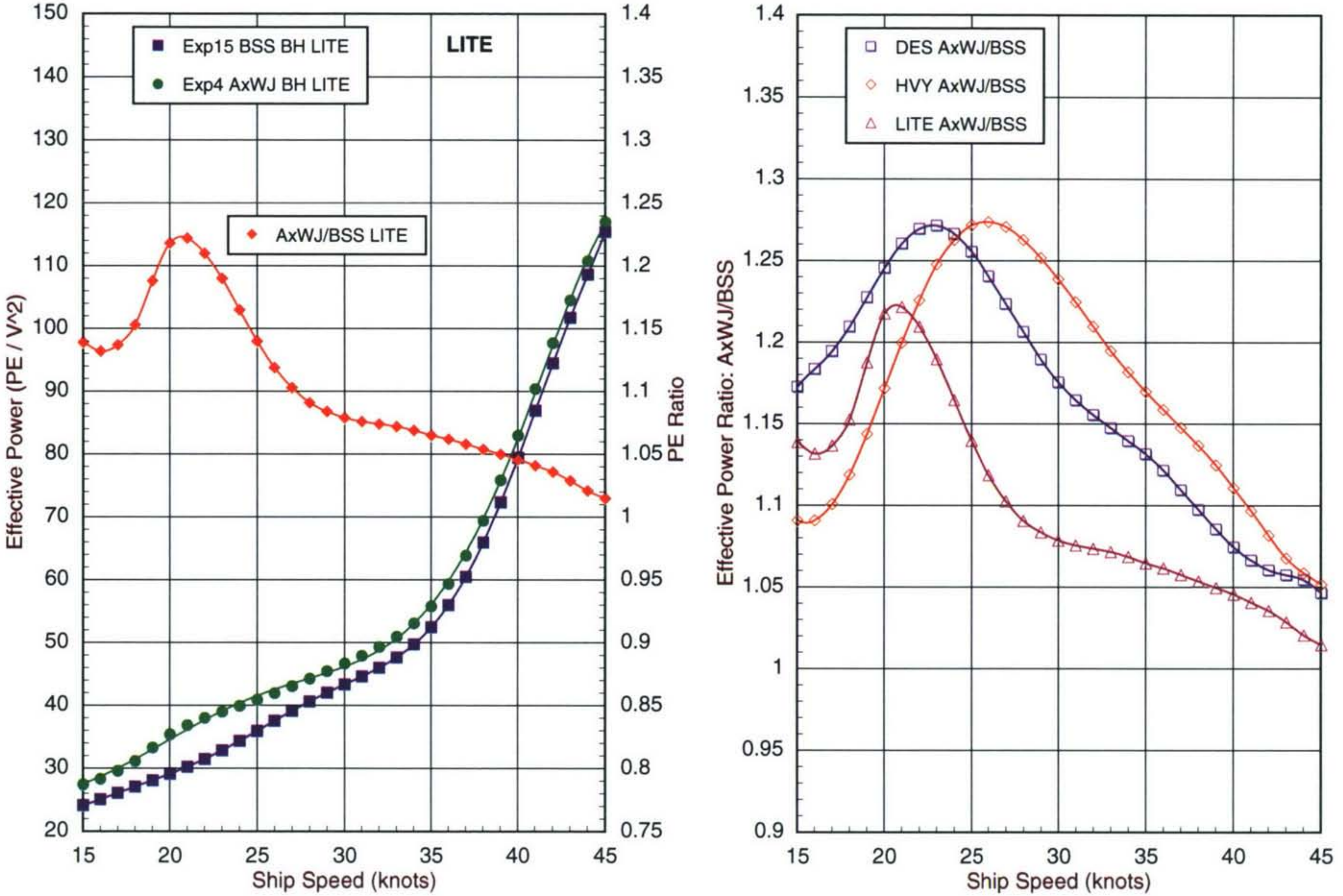


Fig A9. Bare hull PE comparisons between AxWJ and JHSS baseline BSS, three displacements – continued

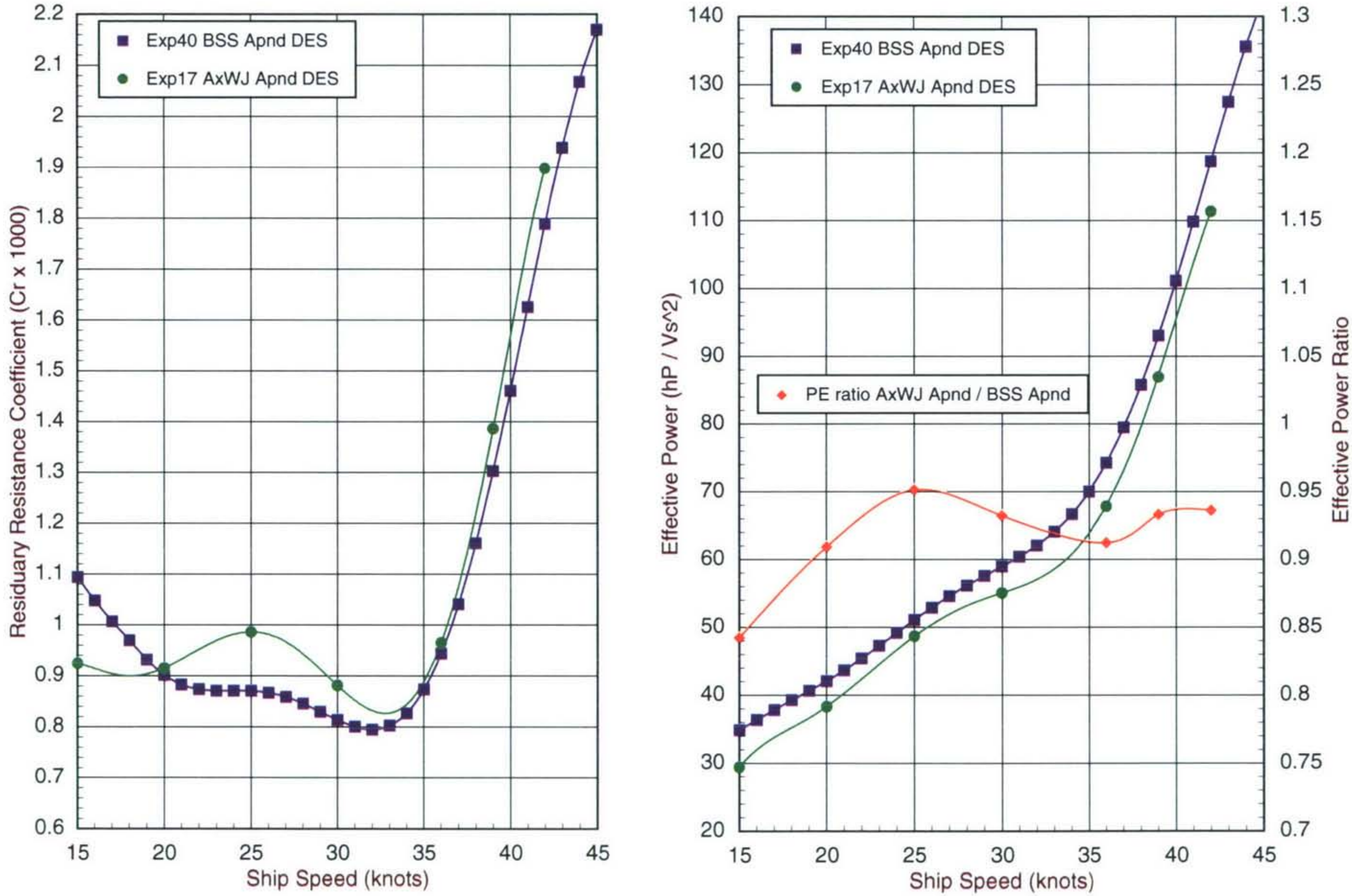


Fig A10. Appended PE comparison between AxWJ (LDV nozzles) and JHSS baseline BSS (shafts & struts, rudders, flap), DES displacement

Table A1. Test Agenda, AxWJ Model 5662 Series 1, Dec 2006 to Feb 2007

Day	Date	Test #	Objective
Mon	12/18		Model rigging continued.
Tue	12/19		Model moved to Carriage 2. Rigging completed. Model ballasted to 3 displacements.
Wed	12/20		Model & Instrumentation installed on Carriage 2
		1	PE set-up, Check-out, Alignment
			Admiral Sullivan Tour
		2	EHP [AxWJ GB HVY BH]
		3	EHP [AxWJ GB DES BH]
Thu	12/21	4	EHP [AxWJ GB LITE BH]
			Shaftlines disassembled at dynos. Drive motors & controls tested.
Fri	12/22		LDV Rig
			Jet Assemblies Installed with dummy hubs. Properly arrange dynamometers. Drive shafts re-manufactured.
Mon	12/25		HOL
Tue	12/26		HOL
Wed	12/27		Pressure gage system assembly and installation.
			Rebuild, Reassemble, & Troubleshoot drive system.
		5	No Loads Conducted* Alternative methods.
Thu	12/28		SI Aft Bearing manufactured and replaced. Cracks in ducts repaired. Jet Assemblies Installed with Rotors. Drive system reassembled. Pressure gage installation continued.
Fri	12/29		LDV Rig
Mon	1/1		HOL
Tue	1/2		LDV and Pressure Systems Installation and Troubleshooting. Jet Assemblies with Rotors Removed/Reinstalled/Modified twice.
Wed	1/3		
Thu	1/4		
Fri	1/5		
Mon	1/8		Model Installed under carriage. Cable and pressure tube installation and check-out.
Tue	1/9		Model removed from Carriage. LDV troubleshooting begun.
Wed	1/10		LDV troubleshooting, Mirror replacement.
Thu	1/11		
Fri	1/12		
Sat	1/13		
Mon	1/15		HOL. LDV mirror installation / troubleshooting.
Tue	1/16	6	Detailed flowrate measured on each jet*
Wed	1/17	7	Blocking Board installed. Bollards conducted on All 4 shafts simultaneously.
		8	DES Powering, 7 speeds. Shaft Forces, Pressures, Station 6 LDV.
Thu	1/18	9	Continuation of DES Powering, Station 6 LDV
		10	Blocking Board reinstalled. Bollards conducted on Individual Shafts.
			Aft (still) camera installed. Dedicated photo runs.
Fri	1/19		Model to drydock. Rig Station 3 (stbd) LDV.
Mon	1/22		Rig Station 3 (stbd) LDV. Reinstall Model.
		11	Station 3 (stbd) LDV, 7 speeds, powered.
Tue	1/23		Model to drydock. Rig Station 3 (port) LDV.
Wed	1/24		Reinstall Model.
		12	Station 3 (port) LDV, 7 speeds, powered.
			Model to drydock.
Thur	1/25		Rig Station 1 (stbd) LDV. Reconfigure pressure gages to CL taps.

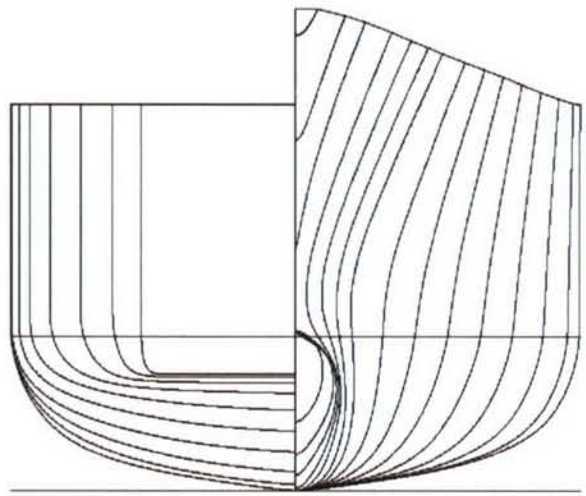
Table A1. Test Agenda, AxWJ Model 5662 Series 1, Dec 2006 to Feb 2007 - continued

Day	Date	Test #	Objective
Fri	1/26		Reinstall model. Pressure gages connected.
			Bollards (partial test, no blocking board) to verify pressure transducer installation.
		13	Station 1 (stbd) LDV, 7 speeds, powered. Measure CL pressures.
Mon	1/29		Model to drydock. Install covers on inlets. Reinstall model.
		14	Station 1 (stbd) LDV, 7 speeds, inlets covered.
Tue	1/30		Model to drydock. Rig Station 1 (port) LDV. Inlets covers removed. Reinstall Model.
		15	Station 1 (port) LDV, 7 speeds, powered.
Wed	1/31		Hi-Def Video camera installed. Dedicated video runs.
		15	Station 1 (port) LDV, powered (continued).
		16	Over/Under Propulsion. DES, 25 & 36 kts.
			Model to drydock. Install covers on inlets.
Thur	2/1		Reinstall Model.
		17	Station 1 (port) LDV, 7 speeds, inlets covered.
			De-Rig
Fri	2/2		

Test	*Rotor RPMs (nominal)
5	No Loads: 1000, 1500, 2000, 2500, 2800, 3000
6	Flow Rate: 1000, 1750, 2500
7, 10	Bollards: 1000, 1500, 1750, 2000, 2500, 2800

Table A2. AxWJ hydrostatic calculations and ship/model test parameters

JHSS Axial Waterjet Hull Gooseneck Bulb 06/12/2006



PRINCIPAL DIMENSIONS

LENGTH (LBP)	= 950.51 ft	(289.71 m)
LENGTH (LWL)	= 979.39 ft	(298.52 m)
BEAM (B_X)	= 104.81 ft	(31.95 m)
DRAFT (T_X)	= 28.27 ft	(8.62 m)
TRIM (+Bow)	= 0.00 ft	(0.00 m)
DISPLACEMENT	= 36491.0 T	(37075. t)
WETTED SURFACE	= 96696 sqft	(8983. sqm)

NONDIMENSIONAL COEFFICIENTS

C_B	= 0.440	C_{VP}	= 0.637	L_E/LWL	= 0.530
C_P	= 0.550	C_{VPF}	= 0.807	L_P/LWL	= 0.000
C_{PF}	= 0.498	C_{VPA}	= 0.858	L_R/LWL	= 0.470
C_{PA}	= 0.612	C_S	= 2.735	FB/LWL	= 0.495
C_{PE}	= 0.521	LWL/B_X	= 9.344	FF/LWL	= 0.563
C_{PR}	= 0.581	B_X/T_X	= 3.707	$100C_\nabla$	= 0.136
C_X	= 0.800	A_T/A_X	= 0.163	$\Delta/(.01 LWL)^3$	= 38.8
C_{WP}	= 0.690	B_T/B_X	= 0.540	i_E	= 3.95
C_{WPF}	= 0.494	T_T/T_X	= 0.247	i_R	= 6.87
C_{WPA}	= 0.902	A_B/A_X	= 0.115	i_B	= 1.25

MODEL SCALE DATA

SCALE RATIO	= 34.121	
LENGTH (LBP)	= 27.86 ft	(8.49 m)
LENGTH (LWL)	= 28.70 ft	(8.75 m)
BEAM (B_X)	= 3.07 ft	(0.94 m)
DRAFT (T_X)	= 0.83 ft	(0.25 m)
DISPLACEMENT	= 2001.1 lbs	(0.91 t)
WETTED SURFACE	= 83.06 sqft	(7.72 sqm)

Table A2. AxWJ hydrostatic calculations and ship/model test parameters

Axial Waterjet (AxWJ) Hull Gooseneck Bulb (GB)	Design (DES) 36491 tons		Heavy (HVY) +10% 40140 tons		Light (LITE) -10% 32841 tons	
Model 5662	SHIP	MODEL	SHIP	MODEL		
MODEL SCALE RATIO	-	34.121	-	34.121	-	34.121
LOA (ft)	977.5	28.648	977.5	28.648	977.5	28.648
LBP (ft)	950.5	27.857	950.5	27.857	950.5	27.857
LWL (ft)	979.4	28.703	948.5	27.798	981.6	28.769
WET SURF HULL(sq ft)	96696	83.055	100380	86.219	92896	79.791
WET SURF APP(sq ft)	0	0.000	0	0.000	0	0.000
TOTAL WET SURF(sq ft)	96696	83.055	100380	86.219	92896	79.791
DISPLACEMENT (ton, lbs)	36491	2000	40140	2200	32841	1800
BOW DRAFT @FP (ft)	28.27	0.829	30.07	0.881	26.47	0.776
STERN DRAFT @AP (ft)	28.27	0.829	30.07	0.881	26.47	0.776
SHIP TRIM (+ft bow up)	0.00	0.000	0.00	0.000	0.00	0.000
TRIM ANGLE (degrees)	0.00		0.00		0.00	
BEAM (ft)	104.8	3.072	105.0	3.076	104.5	3.062
TEMP (F)	59	70	59	70	59	70
RHO	1.9905	1.9362	1.9905	1.9362	1.9905	1.9362
NU	1.2817	1.0552	1.2817	1.0552	1.2817	1.0552
Bow Deck/Keel (ft)	71.6	2.098	71.6	2.098	71.6	2.098
Pos of Hook fwd of FP (ft)	37.0	1.083	0.0	0.000	0.0	0.000
Stern Deck/Keel (ft)	71.6	2.098	71.6	2.098	71.6	2.098
Pos of Hook aft of AP (ft)	17.1	0.500	0.0	0.000	0.0	0.000
BOW HOOK SETTING (ft)		1.269		1.216		1.322
Hook if at FP (ft)	-	1.269	-	1.216	-	1.322
Hook if at AP (ft)	-	1.269	-	1.216	-	1.322
STERN HOOK SETTING (ft)		1.269		1.216		1.322
ROTOR DIA (ft, in)	9.91	3.485	9.91	3.485	9.91	3.485
NUMBER of BLADES	7	7	7	7	7	7
ROTOR ROTATION	INBD	INBD	INBD	INBD	INBD	INBD
SPEED RANGE, min (kts)	15.0	2.57	15.0	2.57	15.0	2.57
Design Speed (kts)	36.0	6.16	36.0	6.16	36.0	6.16
max (kts)	45.0	7.70	45.0	7.70	45.0	7.70
MODEL DISP desired (lbs)		2000		2200		1800
DISP actual (ton, lbs)	36490	2000	40138	2200	32841	1800
MODEL WEIGHT* (lbs)	-	1176	-	1176	-	1176
Floating Platform (lbs)	-	45	-	45	-	45
BALLAST required (lbs)	-	779	-	979	-	579
delta DISP (ton, lbs)			+ 3649	+200 +10.0%	-3649	-200 -10.0%
APPENDAGES, ws (sqft)	0.0	0.000	0.0	0.000	0.0	0.000
none	0.0	0.000	0.0	0.000	0.0	0.000

*Model weight for BH PE Tests was 1176lbs
Model weight for LDV & PD tests was 1310lbs and ballast was adjusted accordingly.

Table A3. AxWJ, Exp2, BH, HVY PE prediction

JHSS AxWJ GB Exp2 BH HVY (PE from RT input with WS no skeg)

	SHIP		MODEL	
LAMBDA			34.121	
LWL	948.5	ft	27.798	ft
S (no Skeg)	100380	ft^2	86.219	ft^2
WT	40140	LT	2200.7	lbs
RHO	1.9905	$(lbf*sec^2)/ft^4$	1.9365	$(lbf*sec^2)/ft^4$
NU	1.2817E-05	ft^2/sec	1.0692E-05	ft^2/sec
Ca			0.0000	

Vs	PE		FRICTIONAL POWER		FN	V-L	1000CR
knots	HP	KW	HP	KW			
14.0	5427.7	4047.4	3426.3	2555.0	0.135	0.455	0.835
15.0	6631.1	4944.8	4179.5	3116.7	0.145	0.487	0.832
16.0	8021.2	5981.4	5033.5	3753.5	0.155	0.520	0.835
17.0	9615.7	7170.4	5994.2	4469.9	0.164	0.552	0.844
18.0	11445.1	8534.6	7067.5	5270.2	0.174	0.584	0.859
19.0	13549.1	10103.5	8259.2	6158.9	0.184	0.617	0.883
20.0	15968.8	11908.0	9575.2	7140.3	0.193	0.649	0.915
21.0	18738.0	13972.9	11021.3	8218.6	0.203	0.682	0.954
22.0	21872.8	16310.6	12603.2	9398.2	0.213	0.714	0.997
23.0	25364.2	18914.1	14326.7	10683.4	0.222	0.747	1.039
24.0	29174.2	21755.2	16197.4	12078.4	0.232	0.779	1.075
25.0	33237.1	24784.9	18221.1	13587.5	0.242	0.812	1.100
26.0	37467.9	27939.8	20403.4	15214.8	0.251	0.844	1.112
27.0	41777.3	31153.3	22750.0	16964.7	0.261	0.877	1.107
28.0	46092.8	34371.4	25266.4	18841.1	0.271	0.909	1.086
29.0	50383.4	37570.9	27958.3	20848.5	0.280	0.942	1.053
30.0	54686.2	40779.5	30831.2	22990.8	0.290	0.974	1.012
31.0	59129.5	44092.8	33890.6	25272.2	0.300	1.007	0.970
32.0	63948.4	47686.3	37142.2	27696.9	0.309	1.039	0.937
33.0	69488.4	51817.5	40591.4	30269.0	0.319	1.072	0.921
34.0	76191.2	56815.8	44243.7	32992.5	0.328	1.104	0.931
35.0	84560.7	63056.9	48104.5	35871.6	0.338	1.136	0.974
36.0	95106.8	70921.2	52179.5	38910.2	0.348	1.169	1.054
37.0	108271.1	80737.7	56473.9	42112.6	0.357	1.201	1.171
38.0	124339.3	92719.8	60993.3	45482.7	0.367	1.234	1.322
39.0	143357.7	106901.8	65743.0	49024.6	0.377	1.266	1.498
40.0	165075.2	123096.5	70728.5	52742.2	0.386	1.299	1.688
41.0	188946.5	140897.4	75955.1	56639.7	0.396	1.331	1.877
42.0	214246.8	159763.8	81428.2	60721.0	0.406	1.364	2.053
43.0	240363.6	179239.1	87153.2	64990.1	0.415	1.396	2.206
44.0	267355.9	199367.3	93135.4	69451.1	0.425	1.429	2.342
45.0	296892.6	221392.8	99380.2	74107.8	0.435	1.461	2.482

Table A4. AxWJ, Exp3, BH, DES PE prediction

JHSS AxWJ GB Exp3 BH DES (PE from RT input with WS no skeg)

	SHIP		MODEL	
LAMBDA			34.121	
LWL	979.4	ft	28.703	ft
S (no Skeg)	96696	ft^2	83.055	ft^2
WT	36491	LT	2000.6	lbs
RHO	1.9905	$(lbf*sec^2)/ft^4$	1.9365	$(lbf*sec^2)/ft^4$
NU	1.2817E-05	ft^2/sec	1.0692E-05	ft^2/sec
Ca			0.0000	

Vs	PE		FRICTIONAL POWER		FN	V-L	1000CR
knots	HP	KW	HP	KW			
14.0	5441.5	4057.7	3287.9	2451.8	0.133	0.447	0.933
15.0	6558.3	4890.6	4010.8	2990.8	0.143	0.479	0.897
16.0	7835.8	5843.2	4830.4	3602.0	0.152	0.511	0.872
17.0	9299.9	6935.0	5752.4	4289.5	0.162	0.543	0.858
18.0	10977.7	8186.1	6782.4	5057.6	0.171	0.575	0.855
19.0	12893.4	9614.6	7926.2	5910.5	0.181	0.607	0.861
20.0	15064.3	11233.4	9189.2	6852.4	0.190	0.639	0.873
21.0	17496.6	13047.2	10577.1	7887.3	0.200	0.671	0.888
22.0	20183.1	15050.6	12095.3	9019.5	0.209	0.703	0.903
23.0	23102.0	17227.2	13749.5	10253.0	0.219	0.735	0.914
24.0	26219.0	19551.5	15545.0	11591.9	0.228	0.767	0.918
25.0	29491.7	21991.9	17487.3	13040.3	0.238	0.799	0.913
26.0	32877.2	24516.5	19581.9	14602.3	0.247	0.831	0.899
27.0	36342.8	27100.9	21834.2	16281.8	0.257	0.863	0.876
28.0	39878.0	29737.0	24249.5	18082.9	0.266	0.895	0.846
29.0	43507.8	32443.8	26833.2	20009.5	0.276	0.927	0.813
30.0	47305.7	35275.8	29590.7	22065.8	0.285	0.959	0.780
31.0	51403.3	38331.5	32527.3	24255.6	0.295	0.991	0.753
32.0	55997.3	41757.2	35648.3	26583.0	0.304	1.023	0.738
33.0	61347.6	45746.9	38959.0	29051.8	0.314	1.054	0.741
34.0	67769.6	50535.8	42464.7	31666.0	0.323	1.086	0.765
35.0	75614.7	56385.9	46170.7	34429.5	0.333	1.118	0.816
36.0	85241.8	63564.8	50082.1	37346.2	0.342	1.150	0.896
37.0	96979.0	72317.2	54204.2	40420.1	0.352	1.182	1.004
38.0	111077.6	82830.6	58542.2	43655.0	0.361	1.214	1.138
39.0	127665.4	95200.1	63101.4	47054.7	0.371	1.246	1.294
40.0	146705.2	109398.1	67886.9	50623.3	0.380	1.278	1.464
41.0	167971.8	125256.6	72903.9	54364.5	0.390	1.310	1.640
42.0	191064.5	142476.8	78157.6	58282.1	0.399	1.342	1.811
43.0	215477.4	160681.5	83653.0	62380.0	0.409	1.374	1.971
44.0	240758.0	179533.3	89395.4	66662.1	0.418	1.406	2.112
45.0	266792.8	198947.4	95389.8	71132.2	0.428	1.438	2.236

Table A5. AxWJ, Exp4, BH, LITE PE prediction

JHSS AxWJ GB Exp4 BH LITE (PE from RT input with WS no skeg)

	SHIP		MODEL	
LAMBDA			34.121	
LWL	981.6	ft	28.769	ft
S (no Skeg)	92896	ft^2	79.791	ft^2
WT	32841	LT	1800.5	lbs
RHO	1.9905	$(lbf*sec^2)/ft^4$	1.9365	$(lbf*sec^2)/ft^4$
NU	1.2817E-05	ft^2/sec	1.0692E-05	ft^2/sec
Ca			0.0000	

Vs	PE		FRICTIONAL POWER		FN	V-L	1000CR
knots	HP	KW	HP	KW			
14.0	5234.1	3903.1	3157.8	2354.8	0.133	0.447	0.936
15.0	6153.3	4588.5	3852.1	2872.5	0.142	0.479	0.844
16.0	7225.7	5388.2	4639.3	3459.5	0.152	0.511	0.781
17.0	8524.9	6357.0	5524.8	4119.8	0.161	0.543	0.756
18.0	10066.1	7506.3	6514.1	4857.6	0.171	0.575	0.754
19.0	11987.8	8939.3	7612.6	5676.7	0.180	0.606	0.789
20.0	14118.6	10528.2	8825.7	6581.3	0.190	0.638	0.819
21.0	16217.4	12093.3	10158.7	7575.3	0.199	0.670	0.809
22.0	18357.6	13689.3	11616.9	8662.7	0.209	0.702	0.783
23.0	20587.9	15352.4	13205.6	9847.4	0.218	0.734	0.751
24.0	22955.0	17117.5	14930.1	11133.4	0.228	0.766	0.718
25.0	25511.0	19023.5	16795.7	12524.5	0.237	0.798	0.690
26.0	28303.9	21106.3	18807.4	14024.7	0.247	0.830	0.669
27.0	31347.9	23376.2	20970.6	15637.8	0.256	0.862	0.652
28.0	34634.7	25827.1	23290.4	17367.7	0.266	0.894	0.639
29.0	38164.1	28459.0	25772.0	19218.1	0.275	0.926	0.629
30.0	41929.4	31266.8	28420.4	21193.1	0.285	0.958	0.619
31.0	45967.5	34278.0	31240.9	23296.3	0.294	0.989	0.612
32.0	50411.4	37591.8	34238.5	25531.6	0.304	1.021	0.611
33.0	55408.9	41318.4	37418.2	27902.8	0.313	1.053	0.619
34.0	61250.9	45674.8	40785.3	30413.6	0.323	1.085	0.644
35.0	68237.9	50885.0	44344.7	33067.8	0.332	1.117	0.690
36.0	76820.1	57284.7	48101.4	35869.2	0.342	1.149	0.762
37.0	87333.2	65124.4	52060.5	38821.5	0.351	1.181	0.862
38.0	100109.9	74651.9	56227.1	41928.5	0.361	1.213	0.989
39.0	115257.8	85947.7	60606.0	45193.9	0.370	1.245	1.140
40.0	132615.3	98891.2	65202.2	48621.3	0.380	1.277	1.303
41.0	151836.1	113224.2	70020.8	52214.5	0.389	1.309	1.469
42.0	172220.6	128424.9	75066.7	55977.3	0.399	1.341	1.622
43.0	193106.3	143999.4	80344.9	59913.2	0.408	1.372	1.755
44.0	214306.4	159808.3	85860.2	64026.0	0.418	1.404	1.866
45.0	236794.3	176577.5	91617.6	68319.3	0.427	1.436	1.971

Table A6. AxWJ, Series 1 PE tests, summary and comparisons

Axial Waterjet GB BH (Model 5662)				Displacement Effects		
	Exp3	Exp2			Exp2/Exp3	Exp4/Exp3
	AxWj	AxWj	AxWj		AxWj	AxWj
	GB	GB	GB		GB	GB
	BH	BH	BH		BH	BH
	DES	**HVY**	**LITE**		HVY/DES	LITE/DES
Vs (kts)	PE (hp)	PE (hp)	PE (hp)	Vs (kts)	PE Ratio	PE Ratio
14	5441	5428	5234	14	0.997	0.962
15	6558	6631	6153	15	1.011	0.938
16	7836	8021	7226	16	1.024	0.922
17	9300	9616	8525	17	1.034	0.917
18	10978	11445	10066	18	1.043	0.917
19	12893	13549	11988	19	1.051	0.930
20	15064	15969	14119	20	1.060	0.937
21	17497	18738	16217	21	1.071	0.927
22	20183	21873	18358	22	1.084	0.910
23	23102	25364	20588	23	1.098	0.891
24	26219	29174	22955	24	1.113	0.876
25	29492	33237	25511	25	1.127	0.865
26	32877	37468	28304	26	1.140	0.861
27	36343	41777	31348	27	1.150	0.863
28	39878	46093	34635	28	1.156	0.869
29	43508	50383	38164	29	1.158	0.877
30	47306	54686	41929	30	1.156	0.886
31	51403	59129	45968	31	1.150	0.894
32	55997	63948	50411	32	1.142	0.900
33	61348	69488	55409	33	1.133	0.903
34	67770	76191	61251	34	1.124	0.904
35	75615	84561	68238	35	1.118	0.902
36	85242	95107	76820	36	1.116	0.901
37	96979	108271	87333	37	1.116	0.901
38	111078	124339	100110	38	1.119	0.901
39	127665	143358	115258	39	1.123	0.903
40	146705	165075	132615	40	1.125	0.904
41	167972	188946	151836	41	1.125	0.904
42	191065	214247	172221	42	1.121	0.901
43	215477	240364	193106	43	1.115	0.896
44	240758	267356	214306	44	1.110	0.890
45	266793	296893	236794	45	1.113	0.888
				Avg:	1.104	0.901

Table A6. AxWJ, Series 1 PE tests, summary and comparisons (continued)

Axial Waterjet Pre-Test Estimate					AxWJ GB BH (Model 5662)		
	Pre-Test AxWJ BB BH DES	GB/BB* BH DES	Pre-Test AxWJ GB BH DES	Pre-Test AxWJ/BSS GB BH DES		Exp3 AxWj GB BH **DES**	AxWJ / Pre-Test GB BH DES
Vs (kts)	PE (hP)	PE Ratio	PE (hP)	PE Ratio	Vs (kts)	PE (hP)	PE Ratio
14	5474	1.040	5691	1.207	14	5441	0.956
		0.999			15	6558	
16	8112	0.972	7888	1.191	16	7836	0.993
		0.957			17	9300	
18	11549	0.949	10961	1.207	18	10978	1.001
		0.947			19	12893	
20	15875	0.948	15050	1.244	20	15064	1.001
		0.951			21	17497	
22	21065	0.955	20117	1.265	22	20183	1.003
		0.959			23	23102	
24	27022	0.962	25996	1.255	24	26219	1.009
		0.965			25	29492	
26	34051	0.967	32913	1.242	26	32877	0.999
		0.968			27	36343	
28	42152	0.970	40867	1.235	28	39878	0.976
		0.971			29	43508	
30	50662	0.973	49279	1.224	30	47306	0.960
		0.975			31	51403	
32	58522	0.977	57171	1.179	32	55997	0.979
		0.979			33	61348	
34	67561	0.981	66299	1.115	34	67770	1.022
35	74290	0.983	73028	1.092	35	75615	1.035
36	82966	0.984	81649	1.074	36	85242	1.044
37	93471	0.985	92035	1.053	37	96979	1.054
38	105867	0.985	104250	1.029	38	111078	1.065
39	120770	0.985	118913	1.010	39	127665	1.074
40	139092	0.985	136943	1.002	40	146705	1.071
		0.985			41	167972	
		0.985			42	191065	
		0.984			43	215477	
		0.982			44	240758	
		0.976			45	266793	

*GB/BB PE ratio determined during JHSS BSS Series 1 tests — Avg: 1.014

Table A6. AxWJ, Series 1 PE tests, summary and comparisons (continued)

Comparisons Between Axial Waterjet Bare Hull and Baseline S&S Bare Hull											
Baseline S&S GB Bare Hull (Model 5653-3)				Axial Waterjet GB Bare Hull (Model 5662)				Axial Waterjet Bare Hull (Model 5662) vs. Baseline S&S Bare Hull (Model 5653-3)			
	Exp14 BSS GB BH **DES**	Exp13 BSS GB BH **HVY**	Exp15 BSS GB BH **LITE**		Exp3 AxWj GB BH **DES**	Exp2 AxWj GB BH **HVY**	AxWj GB BH **LITE**		AxWJ/BSS GB BH **DES**	AxWJ/BSS GB BH **HVY**	AxWJ/BSS GB BH **LITE**
Vs (kts)	PE (hp)	PE (hp)	PE (hp)	Vs (kts)	PE (hp)	PE (hp)	PE (hp)	Vs (kts)	PE Ratio	PE Ratio	PE Ratio
14	4715	4928	4577	14	5441	5428	5234	14	1.154	1.101	1.144
15	5594	6082	5405	15	6558	6631	6153	15	1.172	1.090	1.138
16	6624	7358	6389	16	7836	8021	7226	16	1.183	1.090	1.131
17	7788	8742	7505	17	9300	9616	8525	17	1.194	1.100	1.136
18	9079	10235	8740	18	10978	11445	10066	18	1.209	1.118	1.152
19	10509	11857	10100	19	12893	13549	11988	19	1.227	1.143	1.187
20	12102	13641	11604	20	15064	15969	14119	20	1.245	1.171	1.217
21	13889	15627	13285	21	17497	18738	16217	21	1.260	1.199	1.221
22	15905	17853	15179	22	20183	21873	18358	22	1.269	1.225	1.209
23	18174	20348	17318	23	23102	25364	20588	23	1.271	1.247	1.189
24	20707	23120	19721	24	26219	29174	22955	24	1.266	1.262	1.164
25	23494	26158	22389	25	29492	33237	25511	25	1.255	1.271	1.139
26	26509	29430	25308	26	32877	37468	28304	26	1.240	1.273	1.118
27	29716	32894	28446	27	36343	41777	31348	27	1.223	1.270	1.102
28	33078	36510	31769	28	39878	46093	34635	28	1.206	1.262	1.090
29	36581	40260	35252	29	43508	50383	38164	29	1.189	1.251	1.083
30	40248	44167	38902	30	47306	54686	41929	30	1.175	1.238	1.078
31	44166	48324	42774	31	51403	59129	45968	31	1.164	1.224	1.075
32	48496	52904	46992	32	55997	63948	50411	32	1.155	1.209	1.073
33	53490	58180	51757	33	61348	69488	55409	33	1.147	1.194	1.071
34	59478	64515	57348	34	67770	76191	61251	34	1.139	1.181	1.068
35	66855	72350	64111	35	75615	84561	68238	35	1.131	1.169	1.064
36	76039	82164	72424	36	85242	95107	76820	36	1.121	1.158	1.061
37	87418	94422	82652	37	96979	108271	87333	37	1.109	1.147	1.057
38	101274	109496	95084	38	111078	124339	100110	38	1.097	1.136	1.053
39	117717	127593	109860	39	127665	143358	115258	39	1.085	1.124	1.049
40	136626	148673	126917	40	146705	165075	132615	40	1.074	1.110	1.045
41	157629	172407	145954	41	167972	188946	151836	41	1.066	1.096	1.040
42	180182	198201	166473	42	191065	214247	172221	42	1.060	1.081	1.035
43	203766	225319	187931	43	215477	240364	193106	43	1.057	1.067	1.028
44	228320	252801	210073	44	240758	267356	214306	44	1.054	1.058	1.020
45	254968	282500	233534	45	266793	296893	236794	45	1.046	1.051	1.014
								Avg:	1.164	1.166	1.102

Table A7a. AxWJ, Exp17, LDV nozzles installed, DES PE prediction

JHSS AxWJ GB Exp17 LDV Jets DES (PE from RT input with WS no skeg)

	SHIP		MODEL	
LAMBDA			34.121	
LWL	979.4	ft	28.703	ft
S (no Skeg)	96696	ft^2	83.055	ft^2
WT	36491	LT	2000.6	lbs
RHO	1.9905	$(lbf{*}sec^2)/ft^4$	1.9365	$(lbf{*}sec^2)/ft^4$
NU	1.2817E-05	ft^2/sec	1.0692E-05	ft^2/sec
Ca			0.0000	

Vs	PE		FRICTIONAL POWER		FN	V-L	1000CR
knots	HP	KW	HP	KW			
15.0	6636.3	4948.7	4010.8	2990.8	0.143	0.479	0.925
20.0	15354.4	11449.8	9189.2	6852.4	0.190	0.639	0.916
25.0	30465.9	22718.4	17487.3	13040.3	0.238	0.799	0.987
30.0	49613.9	36997.1	29590.7	22065.8	0.285	0.959	0.882
36.0	88007.9	65627.5	50082.1	37346.2	0.342	1.150	0.966
39.0	132308.4	98662.4	63101.4	47054.7	0.371	1.246	1.387
42.0	196524.9	146548.7	78157.6	58282.1	0.399	1.342	1.899

Table A7b. AxWJ appended (LDV nozzles), comparison to AxWJ bare hull and JHSS baseline BSS fully appended

AxWJ with LDV Nozzles vs AxWJ BH				AxWJ Appended vs BSS Appended			
	Exp3 AxWJ Bare Hull DES	Exp17 AxWJ LDV NOZ DES	NOZ/BH DES		Exp40 BSS Apnd w/Flap DES	Exp17 AxWJ LDV NOZ DES	DES
Vs (kts)	PE (hp)	PE (hp)	PE Ratio	Vs (kts)	PE (hp)	PE (hp)	PE Ratio
15	6558	6636	1.012	15	7868	6636	0.843
20	15064	15354	1.019	20	16868	15354	0.910
25	29492	30466	1.033	25	31987	30466	0.952
30	47306	49614	1.049	30	53157	49614	0.933
36	85242	88008	1.032	36	96351	88008	0.913
39	127665	132308	1.036	39	141663	132308	0.934
42	191065	196525	1.029	42	209631	196525	0.937
		Avg:	1.030			Avg:	0.918

Table A8. AxWJ powering, model-scale rotor force measurements, as tested

AxWJ Model 5662 Faired Rotor T & Q Data, As Tested									
		1	2	3	4	1	2	3	4
VS	Rotor	Port Out	Port In	Stbd In	Stbd Out	Port Out	Port In	Stbd In	Stbd Out
(kts)	RPM	T (lbs)	T (lbs)	T (lbs)	T (lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)
15.04	872.3	1.73	1.71	1.62	2.03	0.95	1.28	1.40	1.21
20.02	1179.6	3.07	3.00	3.04	3.46	1.92	2.37	2.49	2.11
25.05	1483.2	4.73	4.58	4.79	5.24	3.11	3.57	3.78	3.26
30.09	1685.2	6.04	5.83	6.17	6.63	4.05	4.46	4.74	4.17
36.05	2051.4	8.88	8.56	9.16	9.61	6.06	6.33	6.70	6.09
39.10	2355.2	11.74	11.34	12.16	12.57	8.07	8.19	8.53	7.95
42.11	2720.2	15.88	15.37	16.45	16.75	10.90	10.88	10.95	10.47

AxWJ Model 5662 T & Q Data Faired Curvefits vs Rotor RPM								
	1	2	3	4	1	2	3	4
Rotor	Port Out	Port In	Stbd In	Stbd Out	Port Out	Port In	Stbd In	Stbd Out
RPM	T (lbs)	T (lbs)	T (lbs)	T (lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)
850	1.64	1.63	1.53	1.94	0.89	1.20	1.33	1.16
1000	2.25	2.21	2.17	2.59	1.32	1.72	1.83	1.55
1250	3.43	3.34	3.41	3.84	2.17	2.63	2.77	2.35
1500	4.83	4.68	4.90	5.34	3.18	3.64	3.85	3.33
1750	6.49	6.27	6.65	7.11	4.37	4.76	5.07	4.48
2000	8.44	8.14	8.70	9.16	5.76	6.05	6.41	5.80
2250	10.69	10.32	11.06	11.49	7.34	7.51	7.87	7.28
2500	13.29	12.84	13.77	14.14	9.13	9.19	9.46	8.91
2750	16.25	15.73	16.83	17.12	11.16	11.12	11.16	10.68

AxWJ Model 5662 Faired Rotor T & Q Data at Incremental Full Scale Speeds									
		1	2	3	4	1	2	3	4
VS	Rotor	Port Out	Port In	Stbd In	Stbd Out	Port Out	Port In	Stbd In	Stbd Out
(kts)	RPM	T (lbs)	T (lbs)	T (lbs)	T (lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)
15	870.8	1.72	1.70	1.62	2.03	0.95	1.27	1.39	1.21
20	1179.0	3.07	3.00	3.04	3.46	1.91	2.37	2.49	2.10
25	1479.2	4.71	4.56	4.76	5.21	3.09	3.55	3.76	3.24
30	1684.0	6.03	5.83	6.16	6.62	4.04	4.45	4.73	4.16
36	2044.0	8.81	8.50	9.09	9.54	6.02	6.29	6.66	6.05
39	2345.9	11.65	11.24	12.06	12.47	8.00	8.13	8.47	7.89
42	2706.4	15.71	15.20	16.27	16.58	10.79	10.77	10.86	10.37

Table A9. AxWJ, faired model-scale rotor forces data, over- and under-propelled, 25 and 36 knots, as tested

25 knots Ship Speed: Over- & Under-Propelled Faired Rotor Forces Data, Test 16										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	1612	2.95	6.08	5.59	5.72	5.94	3.81	4.45	4.28	3.78
+5% RPM	1539	4.55	5.53	5.03	5.17	5.34	3.48	4.09	3.90	3.43
Desired Fd	1466	**6.06**	5.00	4.50	4.71	4.78	3.17	3.71	3.55	3.07
-5% RPM	1392	7.49	4.49	3.99	4.32	4.24	2.88	3.33	3.21	2.70
-10% RPM	1319	8.84	4.01	3.51	4.02	3.73	2.61	2.93	2.89	2.32

36 knots Ship Speed: Over- & Under-Propelled Faired Rotor Forces Data, Test 16										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	2245	5.64	11.25	10.62	11.81	11.36	7.61	7.58	7.80	7.24
+5% RPM	2143	8.76	10.17	9.55	10.36	10.21	6.86	7.01	7.11	6.61
Desired Fd	2041	**11.65**	9.15	8.50	9.00	9.12	6.14	6.47	6.46	5.99
-5% RPM	1938	14.30	8.19	7.48	7.74	8.10	5.45	5.94	5.84	5.38
-10% RPM	1836	16.72	7.30	6.48	6.57	7.13	4.78	5.45	5.27	4.78

Table A9. AxWJ, faired rotor forces data, over- and under-propelled, 25 and 36 knots, as tested – continued

Differences in Model Rotor Forces Derrived from Traditional Method Powering Test and from Cross-Plotted Over/Under Propelled Test, 25 and 36 knots							
	VS (kts)	Rotor RPM	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Total T (lbs)
Traditional	25	1479	4.71	4.56	4.76	5.21	19.24
Over/Under	25	1466	5.00	4.50	4.71	4.78	18.99
Difference		-0.9%	6.2%	-1.3%	-1.2%	-8.3%	-1.3%
	VS (kts)	Rotor RPM	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)	Total Q (in-lbs)
Traditional	25	1479	3.09	3.55	3.76	3.24	13.64
Over/Under	25	1466	3.17	3.71	3.55	3.07	13.49
Difference		-0.9%	2.4%	4.6%	-5.6%	-5.4%	-1.1%
	VS (kts)	Rotor RPM	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Total T (lbs)
Traditional	36	2044	8.81	8.50	9.09	9.54	35.95
Over/Under	36	2041	9.15	8.50	9.00	9.12	35.77
Difference		-0.2%	3.8%	0.0%	-1.0%	-4.4%	-0.5%
	VS (kts)	Rotor RPM	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)	Total Q (in-lbs)
Traditional	36	2044	6.02	6.29	6.66	6.05	25.02
Over/Under	36	2041	6.14	6.47	6.46	5.99	25.05
Difference		-0.2%	2.0%	2.8%	-3.0%	-1.1%	0.1%

Table A10. AxWJ, estimated model-scale rotor forces, over- and under-propelled, for speeds not tested

15 knots ESTIMATED Over- & Under-Propulsion Rotor Forces										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	958	1.46	2.13	2.11	1.41	2.45	1.12	1.83	1.62	1.70
+5% RPM	915	1.97	1.92	1.90	1.50	2.23	1.03	1.55	1.50	1.45
Desired Fd	**871**	**2.44**	**1.72**	**1.70**	**1.62**	**2.02**	**0.95**	**1.27**	**1.38**	**1.21**
-5% RPM	827	2.88	1.52	1.51	1.76	1.83	0.87	0.99	1.27	0.96
-10% RPM	784	3.29	1.33	1.33	1.94	1.64	0.81	0.70	1.17	0.70

20 knots ESTIMATED Over- & Under-Propulsion Rotor Forces										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	1297	2.13	3.79	3.72	3.32	4.22	2.30	3.04	2.94	2.73
+5% RPM	1238	3.13	3.42	3.35	3.16	3.83	2.10	2.71	2.71	2.42
Desired Fd	**1179**	**4.07**	**3.07**	**3.00**	**3.04**	**3.46**	**1.92**	**2.37**	**2.48**	**2.11**
-5% RPM	1120	4.95	2.73	2.66	2.98	3.10	1.75	2.02	2.27	1.79
-10% RPM	1061	5.78	2.41	2.34	2.96	2.77	1.59	1.67	2.07	1.47

30 knots ESTIMATED Over- & Under-Propulsion Rotor Forces										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	1852	4.20	7.42	7.25	7.89	8.14	4.93	5.22	5.72	4.95
+5% RPM	1768	6.36	6.71	6.52	6.97	7.36	4.48	4.84	5.21	4.56
Desired Fd	**1684**	**8.40**	**6.03**	**5.83**	**6.16**	**6.62**	**4.05**	**4.45**	**4.74**	**4.17**
-5% RPM	1600	10.33	5.37	5.16	5.45	5.91	3.64	4.05	4.29	3.77
-10% RPM	1516	12.15	4.75	4.53	4.85	5.24	3.27	3.63	3.86	3.36

Table A10. AxWJ, estimated model-scale rotor forces, over- and under-propelled, for speeds not tested - continued

39 knots ESTIMATED Over- & Under-Propulsion Rotor Forces										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	2581	4.84	14.51	13.86	15.98	15.51	9.92	9.59	10.28	9.40
+5% RPM	2463	9.30	13.04	12.54	13.96	13.95	8.94	8.84	9.35	8.63
Desired Fd	**2346**	**13.45**	**11.64**	**11.25**	**12.06**	**12.47**	**8.00**	**8.13**	**8.47**	**7.88**
-5% RPM	2229	17.29	10.33	9.99	10.29	11.08	7.11	7.44	7.64	7.14
-10% RPM	2111	20.82	9.11	8.77	8.64	9.77	6.25	6.79	6.86	6.42

42 knots ESTIMATED Over- & Under-Propulsion Rotor Forces										
			1	2	3	4	1	2	3	4
	Rotor RPM	FD (lbs)	Port Out T (lbs)	Port In T (lbs)	Stbd In T (lbs)	Stbd Out T (lbs)	Port Out Q (in-lbs)	Port In Q (in-lbs)	Stbd In Q (in-lbs)	Stbd Out Q (in-lbs)
+10% RPM	2977	3.12	19.63	18.46	21.73	20.70	13.28	12.70	13.31	12.22
+5% RPM	2841	9.45	17.61	16.81	18.92	18.58	12.01	11.71	12.05	11.28
Desired Fd	**2706**	**15.37**	**15.70**	**15.20**	**16.27**	**16.57**	**10.78**	**10.76**	**10.85**	**10.36**
-5% RPM	2571	20.87	13.90	13.64	13.79	14.68	9.61	9.86	9.72	9.46
-10% RPM	2435	25.96	12.22	12.12	11.48	12.89	8.49	9.00	8.66	8.58

Table A11. AxWJ model-scale rotor forces estimated at corrected ship propulsion point

JHSS AxWJ Powering Data Estimate (Using Over/Under Data) at Corrected Ship Propulsion Point (Corrected FD)										
		Corrected	1	2	3	4	1	2	3	4
VS	Rotor	FD	Port Out	Port In	Stbd In	Stbd Out	Port Out	Port In	Stbd In	Stbd Out
(knots)	RPM	(lbs)	T (lbs)	T (lbs)	T (lbs)	T (lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)
15	886	2.28	1.79	1.77	1.63	2.09	0.98	1.37	1.42	1.29
20	1196	3.81	3.17	3.10	3.07	3.56	1.97	2.46	2.54	2.20
25	1485	5.67	5.14	4.64	4.82	4.93	3.25	3.81	3.64	3.16
30	1707	7.86	6.21	6.01	6.37	6.82	4.16	4.56	4.86	4.27
36	2068	10.90	9.42	8.78	9.36	9.41	6.33	6.61	6.63	6.15
39	2372	12.58	11.94	11.53	12.46	12.79	8.20	8.28	8.66	8.04
42	2730	14.37	16.03	15.48	16.72	16.91	10.99	10.92	11.06	10.52

JHSS AxWJ Powering (Using Over/Under Data) at Ship Propulsion Point as Tested (Original FD)										
		Original	1	2	3	4	1	2	3	4
VS	Rotor	FD	Port Out	Port In	Stbd In	Stbd Out	Port Out	Port In	Stbd In	Stbd Out
(knots)	RPM	(lbs)	T (lbs)	T (lbs)	T (lbs)	T (lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)	Q (in-lbs)
15	871	2.44	1.72	1.70	1.62	2.02	0.95	1.27	1.38	1.21
20	1179	4.07	3.07	3.00	3.04	3.46	1.92	2.37	2.48	2.11
25	1466	6.06	5.00	4.50	4.71	4.78	3.17	3.71	3.55	3.07
30	1684	8.40	6.03	5.83	6.16	6.62	4.05	4.45	4.74	4.17
36	2041	11.65	9.15	8.50	9.00	9.12	6.14	6.47	6.46	5.99
39	2346	13.45	11.64	11.25	12.06	12.47	8.00	8.13	8.47	7.88
42	2706	15.37	15.70	15.20	16.27	16.57	10.78	10.76	10.85	10.36

Comparison of AxWJ Corrected Powering Data vs. As Tested Powering Data										
			1	2	3	4	1	2	3	4
VS	RPM	FD	Port Out	Port In	Stbd In	Stbd Out	Port Out	Port In	Stbd In	Stbd Out
(kts)	Δ (%)	Δ (%)	ΔT (%)	ΔT (%)	ΔT (%)	ΔT (%)	ΔQ (%)	ΔQ (%)	ΔQ (%)	ΔQ (%)
15	1.7	-6.5	4.1	4.0	0.9	3.5	2.9	7.6	2.8	7.1
20	1.4	-6.5	3.2	3.2	0.9	3.0	2.6	4.0	2.5	4.2
25	1.3	-6.5	2.8	3.1	2.5	3.1	2.6	2.7	2.6	3.2
30	1.3	-6.5	3.0	3.2	3.4	3.0	2.8	2.4	2.7	2.6
36	1.3	-6.5	2.9	3.3	4.0	3.1	3.1	2.2	2.7	2.8
39	1.1	-6.5	2.5	2.5	3.3	2.5	2.5	1.9	2.2	2.1
42	0.9	-6.5	2.1	1.8	2.7	2.1	1.9	1.5	1.9	1.5
Avg:	1.3	-6.5	2.8				2.9			

Table A12. AxWJ Model 5662 resistance and powering measurement uncertainties

25 knot Ship Speed							
	Units	Nominal	Bias	Precision	Uncertainty		Four Shafts
Measurement		Mean	Error	Error	(units)	(percent)	(percent)
			±	±	±	±	±
Speed	ft/sec	7.24	0.002	0.001	0.002	0.03	-
Resistance	lbf	15.15	0.059	0.036	0.069	**0.46**	-
INbd Prop Shaft Rate	RPM	1484.21	0.009	0.911	0.911	0.06	-
OUTbd Prop Shaft Rate	RPM	1483.23	0.009	1.234	1.234	0.08	0.07
INbd Shaft Thrust - combined	lbf	8.76	0.057	0.037	0.068	0.78	-
OUTbd Shaft Thrust - combined	lbf	9.99	0.057	0.042	0.071	0.71	0.74
INbd Shaft Torque - combined	lbf-in	7.33	0.094	0.146	0.174	2.37	-
OUTbd Shaft Torque - combined	lbf-in	6.55	0.094	0.079	0.123	1.88	2.12
INbd Shaft Power - combined	hP	0.173	0.0022	0.0034	0.0041	2.37	-
OUTbd Shaft Power - combined	hP	0.154	0.0022	0.0019	0.0029	1.88	**2.13**

36 knot Ship Speed							
	Units	Nominal	Bias	Precision	Uncertainty		Four Shafts
Measurement		Mean	Error	Error	(units)	(percent)	(percent)
			±	±	±	±	±
Speed	ft/sec	10.41	0.003	0.000	0.003	0.03	-
Resistance	lbf	29.75	0.063	0.082	0.103	**0.35**	-
INbd Prop Shaft Rate	RPM	2053.83	0.011	2.407	2.407	0.12	-
OUTbd Prop Shaft Rate	RPM	2053.12	0.011	1.860	1.860	0.09	0.10
INbd Shaft Thrust - combined	lbf	16.98	0.060	0.033	0.068	0.40	-
OUTbd Shaft Thrust - combined	lbf	18.49	0.060	0.061	0.085	0.46	0.43
INbd Shaft Torque - combined	lbf-in	12.97	0.096	0.172	0.197	1.52	-
OUTbd Shaft Torque - combined	lbf-in	12.43	0.096	0.182	0.206	1.66	1.59
INbd Shaft Power - combined	hP	0.423	0.0031	0.0056	0.0064	1.52	-
OUTbd Shaft Power - combined	hP	0.405	0.0031	0.0059	0.0067	1.66	**1.59**

Table A13. AxWJ BH (unpowered), dynamic sinkage and pitch, at three ship displacements

	JHSS Axial Water Jet (AxWJ), Gooseneck Bulb (GB), Bare Hull (BH)								
	Heavy (HVY)			Design (DES)			Light (LITE)		
VS (Knots)	Sinkage FP (ft)	Sinkage AP (ft)	Pitch Angle (degrees)	Sinkage FP (ft)	Sinkage AP (ft)	Pitch Angle (degrees)	Sinkage FP (ft)	Sinkage AP (ft)	Pitch Angle (degrees)
15	0.43	0.05	-0.02	0.50	0.14	-0.02	0.48	0.09	-0.02
16	0.50	0.07	-0.03	0.57	0.16	-0.03	0.56	0.13	-0.03
17	0.58	0.08	-0.03	0.63	0.13	-0.03	0.62	0.12	-0.03
18	0.67	0.07	-0.04	0.68	0.09	-0.04	0.67	0.09	-0.03
19	0.77	0.08	-0.04	0.75	0.06	-0.04	0.73	0.07	-0.04
20	0.88	0.10	-0.05	0.82	0.06	-0.05	0.80	0.06	-0.04
21	0.98	0.13	-0.05	0.91	0.07	-0.05	0.88	0.06	-0.05
22	1.09	0.18	-0.05	1.01	0.11	-0.05	0.98	0.08	-0.05
23	1.20	0.24	-0.06	1.12	0.16	-0.06	1.10	0.10	-0.06
24	1.30	0.30	-0.06	1.24	0.21	-0.06	1.22	0.12	-0.07
25	1.41	0.35	-0.06	1.37	0.25	-0.07	1.36	0.14	-0.07
26	1.53	0.40	-0.07	1.51	0.28	-0.07	1.51	0.15	-0.08
27	1.66	0.43	-0.07	1.67	0.29	-0.08	1.68	0.14	-0.09
28	1.80	0.44	-0.08	1.84	0.27	-0.09	1.86	0.11	-0.11
29	1.97	0.44	-0.09	2.03	0.24	-0.11	2.06	0.07	-0.12
30	2.17	0.42	-0.11	2.24	0.20	-0.12	2.28	0.02	-0.14
31	2.38	0.40	-0.12	2.46	0.15	-0.14	2.51	-0.03	-0.15
32	2.61	0.38	-0.13	2.70	0.11	-0.16	2.75	-0.08	-0.17
33	2.84	0.38	-0.15	2.94	0.09	-0.17	2.99	-0.10	-0.19
34	3.06	0.42	-0.16	3.17	0.12	-0.18	3.22	-0.09	-0.20
35	3.26	0.52	-0.17	3.37	0.20	-0.19	3.42	-0.03	-0.21
36	3.41	0.69	-0.16	3.53	0.35	-0.19	3.58	0.10	-0.21
37	3.48	0.95	-0.15	3.63	0.59	-0.18	3.68	0.31	-0.20
38	3.46	1.32	-0.13	3.64	0.94	-0.16	3.69	0.61	-0.19
39	3.33	1.81	-0.09	3.54	1.39	-0.13	3.61	1.02	-0.16
40	3.06	2.43	-0.04	3.33	1.95	-0.08	3.41	1.53	-0.11
41	2.67	3.15	0.03	2.99	2.62	-0.02	3.10	2.13	-0.06
42	2.17	3.95	0.11	2.54	3.36	0.05	2.68	2.81	0.01
43	1.58	4.79	0.19	2.00	4.15	0.13	2.19	3.53	0.08
44	0.99	5.59	0.28	1.44	4.93	0.21	1.68	4.23	0.15
45	0.50	6.26	0.35	0.93	5.65	0.29	1.24	4.85	0.22

Table A14. AxWJ, dynamic sinkage and pitch, powered vs. unpowered

	JHSS Axial Water Jet (AxWJ), Design (DES) Displacement					
	Bare Hull (Unpowered)			Waterjet Powered		
VS (Knots)	Sinkage FP (ft)	Sinkage AP (ft)	Pitch Angle (degrees)	Sinkage FP (ft)	Sinkage AP (ft)	Pitch Angle (degrees)
15	0.50	0.14	-0.02	0.27	0.36	0.00
16	0.57	0.16	-0.03	0.39	0.28	0.01
17	0.63	0.13	-0.03	0.46	0.28	0.01
18	0.68	0.09	-0.04	0.50	0.33	0.01
19	0.75	0.06	-0.04	0.53	0.43	0.00
20	0.82	0.06	-0.05	0.55	0.53	0.00
21	0.91	0.07	-0.05	0.58	0.64	0.00
22	1.01	0.11	-0.05	0.62	0.73	0.00
23	1.12	0.16	-0.06	0.67	0.81	0.00
24	1.24	0.21	-0.06	0.75	0.87	0.00
25	1.37	0.25	-0.07	0.85	0.91	0.00
26	1.51	0.28	-0.07	0.97	0.92	-0.01
27	1.67	0.29	-0.08	1.12	0.92	-0.01
28	1.84	0.27	-0.09	1.29	0.90	-0.02
29	2.03	0.24	-0.11	1.48	0.88	-0.03
30	2.24	0.20	-0.12	1.69	0.85	-0.05
31	2.46	0.15	-0.14	1.90	0.84	-0.06
32	2.70	0.11	-0.16	2.12	0.85	-0.08
33	2.94	0.09	-0.17	2.32	0.89	-0.09
34	3.17	0.12	-0.18	2.51	0.97	-0.10
35	3.37	0.20	-0.19	2.66	1.11	-0.10
36	3.53	0.35	-0.19	2.77	1.31	-0.09
37	3.63	0.59	-0.18	2.82	1.59	-0.08
38	3.64	0.94	-0.16	2.79	1.95	-0.05
39	3.54	1.39	-0.13	2.67	2.40	-0.01
40	3.33	1.95	-0.08	2.44	2.96	0.04
41	2.99	2.62	-0.02	2.08	3.61	0.10
42	2.54	3.36	0.05	1.56	4.38	0.17
43	2.00	4.15	0.13			
44	1.44	4.93	0.21			
45	0.93	5.65	0.29			

Table A15. Model-scale powering comparison: AxWJ vs. BSS

JHSS Axial Waterjet (AxWJ) Model-Scale Powering at Corrected Ship Propulsion Point										
VS (knots)	Rotor RPM	INBD/Shaft T (lbs)	OTBD/Shaft T (lbs)	Total T (lbs)	INBD/Shaft Q (in-lbs)	OTBD/Shaft Q (in-lbs)	Total Q (in-lbs)	INBD/Shaft (hP)	OTBD/Shaft (hP)	Total SHP
15	886	1.67	1.94	7.22	1.39	1.13	5.06	0.020	0.016	0.07
20	1196	3.08	3.36	12.89	2.50	2.08	9.17	0.048	0.039	0.17
25	1485	4.73	5.03	19.53	3.73	3.21	13.86	0.088	0.076	0.33
30	1707	6.19	6.51	25.40	4.71	4.22	17.86	0.128	0.114	0.48
36	2068	9.07	9.41	36.96	6.62	6.24	25.72	0.217	0.205	0.84
39	2372	11.99	12.36	48.71	8.47	8.12	33.18	0.319	0.306	1.25
42	2730	16.10	16.47	65.14	10.99	10.76	43.49	0.476	0.466	1.88

JHSS Baseline Shaft&Strut (BSS) Model-Scale Powering at Ship Propulsion Point										
VS (knots)	Propeller RPM	INBD/Shaft T (lbs)	OTBD/Shaft T (lbs)	Total T (lbs)	INBD/Shaft Q (in-lbs)	OTBD/Shaft Q (in-lbs)	Total Q (in-lbs)	INBD/Shaft (hP)	OTBD/Shaft (hP)	Total SHP
15	322	1.36	0.90	4.52	2.54	2.40	9.88	0.013	0.012	0.05
20	419	2.21	1.44	7.30	4.40	3.88	16.56	0.029	0.026	0.11
25	522	3.44	2.27	11.42	6.96	5.81	25.54	0.058	0.048	0.21
30	620	4.78	3.18	15.92	9.87	8.03	35.80	0.097	0.079	0.35
36	740	6.95	4.89	23.68	14.62	12.08	53.40	0.172	0.142	0.63
39	818	9.23	6.86	32.18	19.04	16.07	70.22	0.247	0.208	0.91
42	911	12.54	9.77	44.62	24.68	21.32	92.00	0.357	0.308	1.33

Model-Scale Powering Comparison: Axial Waterjet (AxWJ) vs. Baseline Shaft&Strut (BSS)										
VS (knots)	RPM Δ (%)	INBD T Δ (%)	OTBD T Δ (%)	Total T Δ (%)	INBD Q Δ (%)	OTBD Q Δ (%)	Total Q Δ (%)	INBD hp Δ (%)	INBD hp Δ (%)	Total SHP Δ (%)
15	175.6	22.9	115.5	59.8	-45.1	-52.7	-48.8	51.2	30.2	41.0
20	185.3	39.4	133.6	76.6	-43.1	-46.3	-44.6	62.4	53.1	58.1
25	184.6	37.5	121.7	71.0	-46.5	-44.8	-45.7	52.4	57.0	54.5
30	175.5	29.5	104.8	59.6	-52.3	-47.5	-50.1	31.5	44.6	37.4
36	179.4	30.5	92.5	56.1	-54.7	-48.3	-51.8	26.5	44.3	34.6
39	190.0	29.9	80.2	51.4	-55.5	-49.5	-52.7	29.0	46.6	37.1
42	199.6	28.4	68.6	46.0	-55.5	-49.5	-52.7	33.4	51.2	41.7
Avg (%):	184.3	31.2	102.4	60.1	-50.4	-48.4	-49.5	40.9	46.7	43.5

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APPENDIX B

AxWJ Model 5662 Photographs

AxWJ MODEL 5662 PHOTOGRAPHS

Fig B1. AxWJ Model 5662: construction and hardware installation

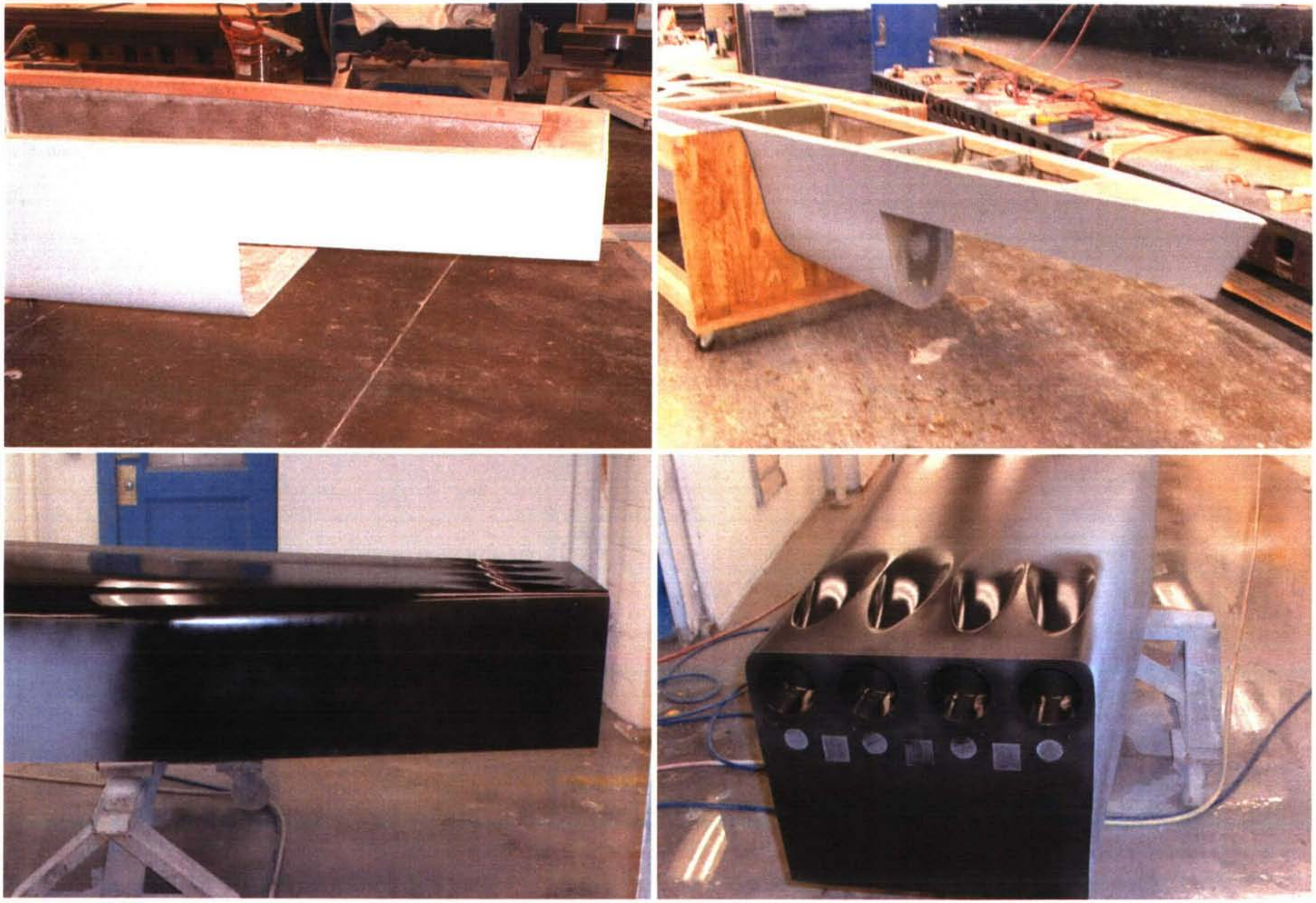

Fig B1. AxWJ Model 5662: construction and hardware installation - continued

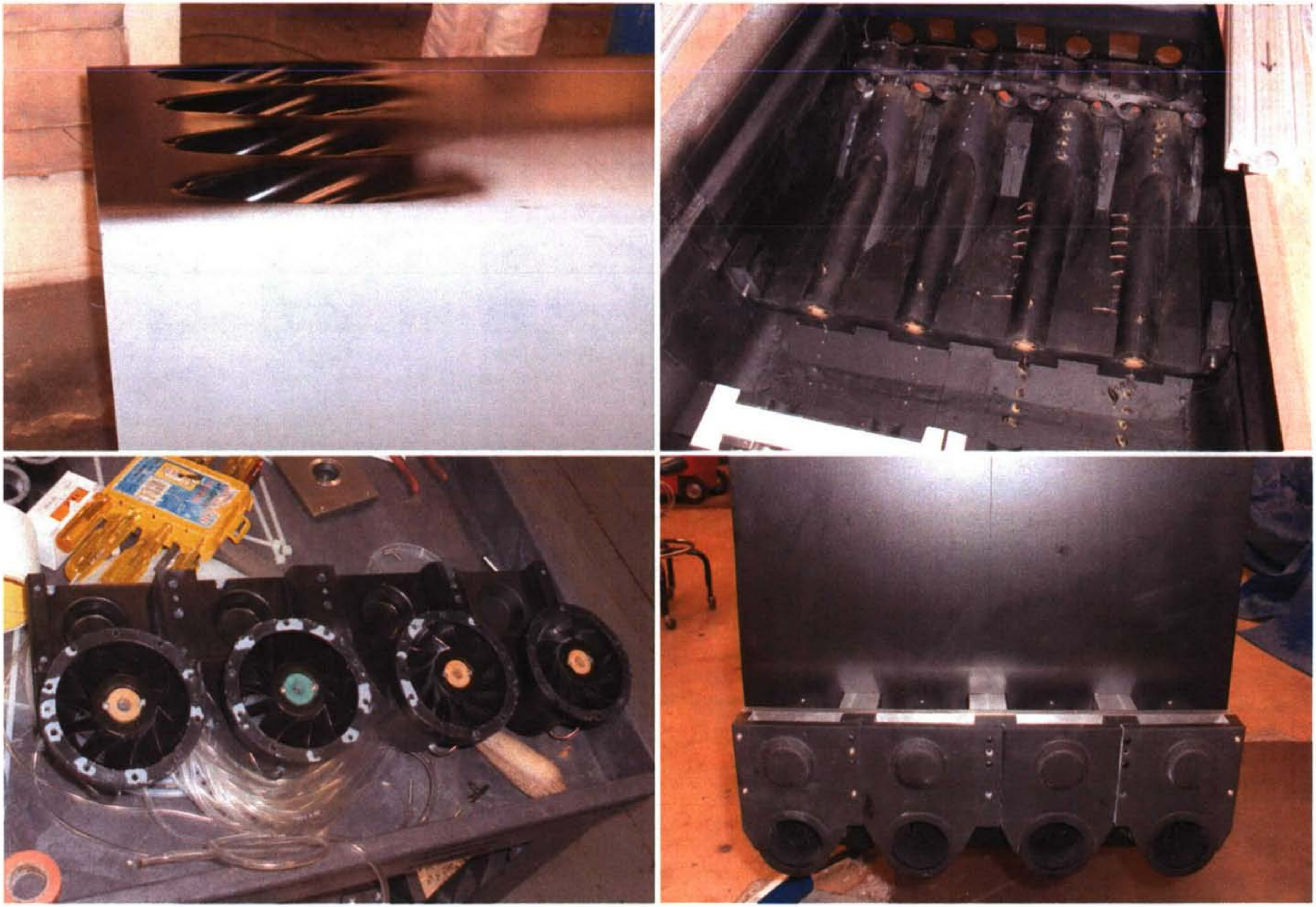

Fig B1. Pre-Test, construction and hardware installation - continued

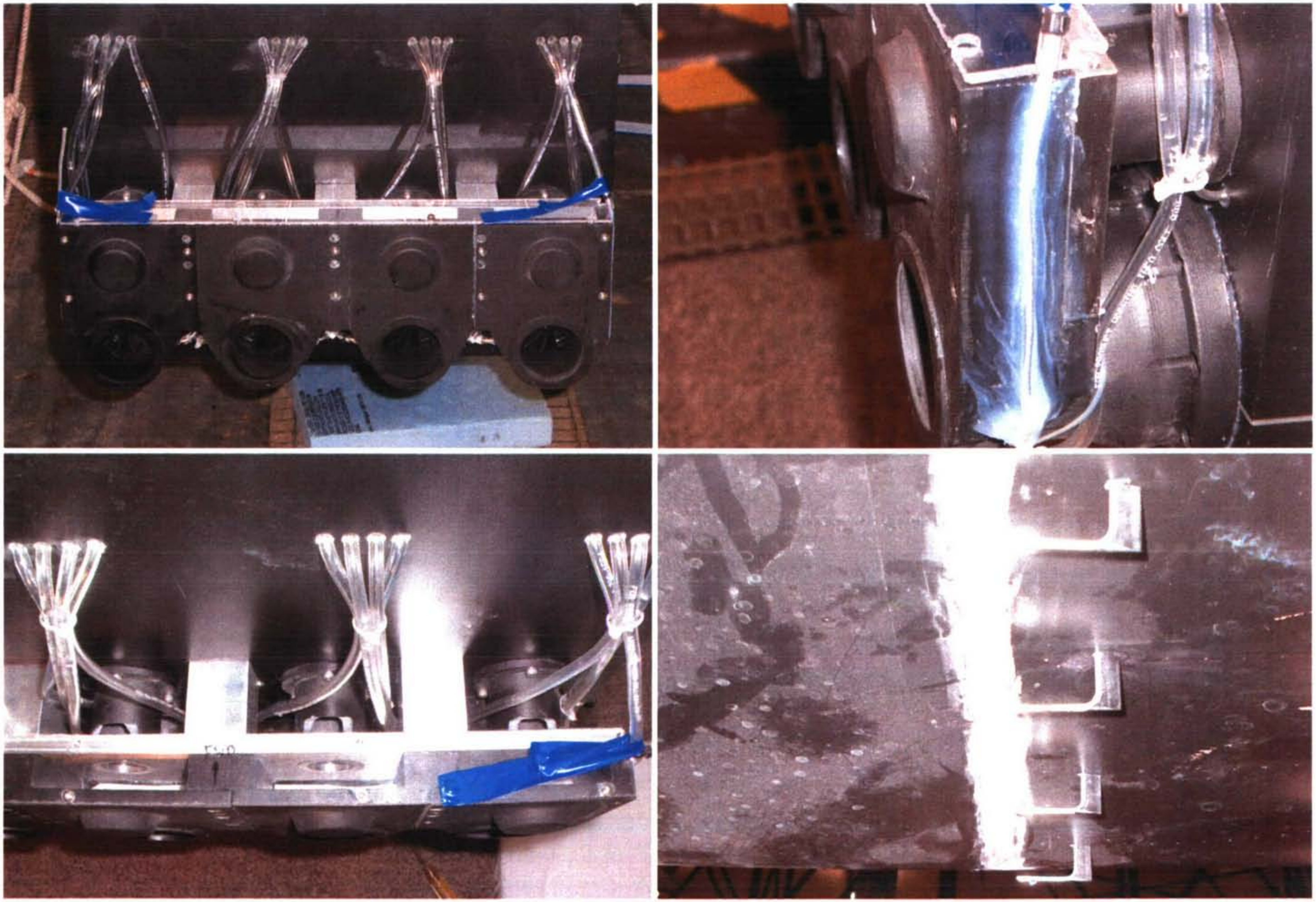

Fig B1. AxWJ Model 5662: construction and hardware installation - continued

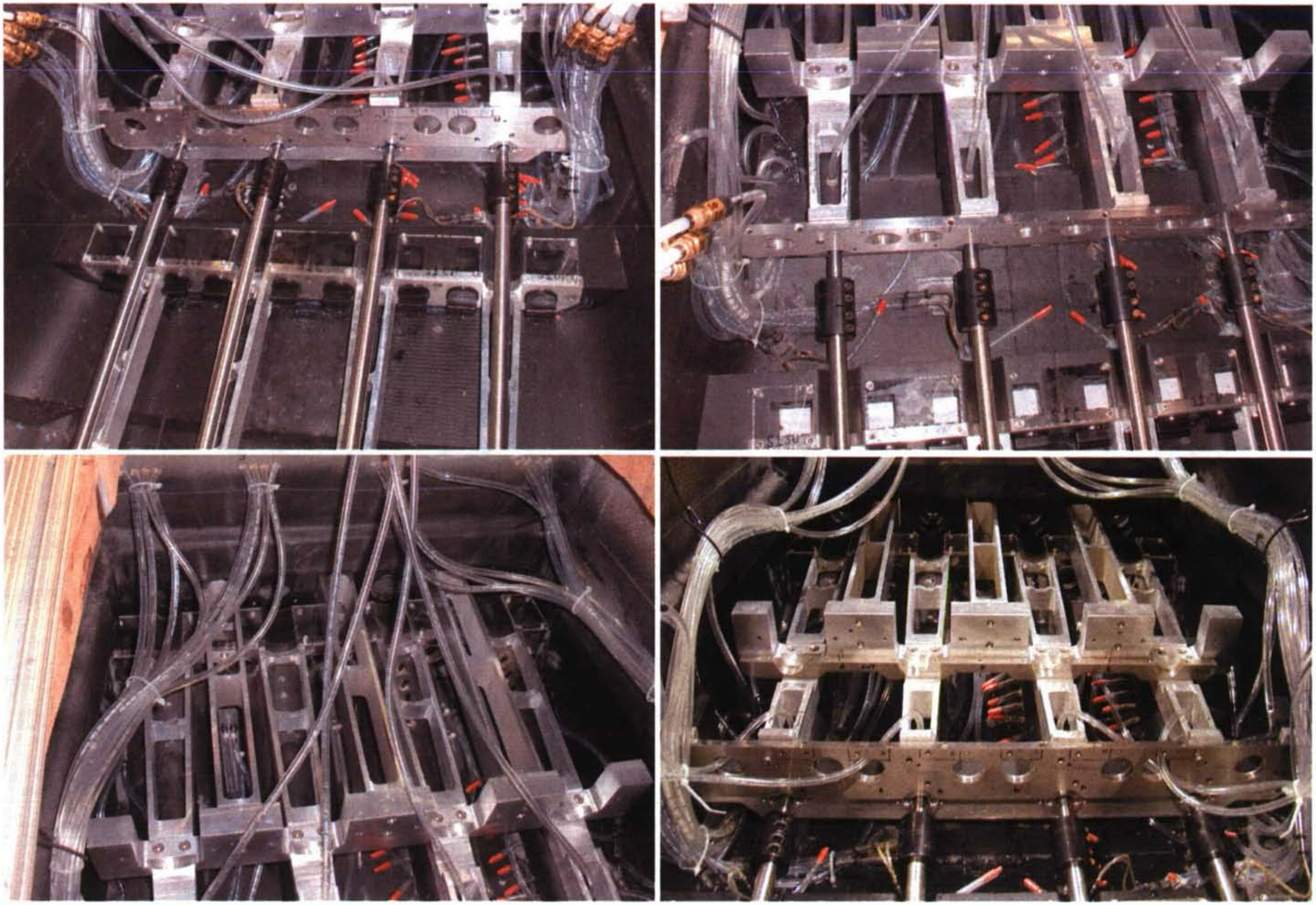

Fig B1. AxWJ Model 5662: construction and hardware installation - continued

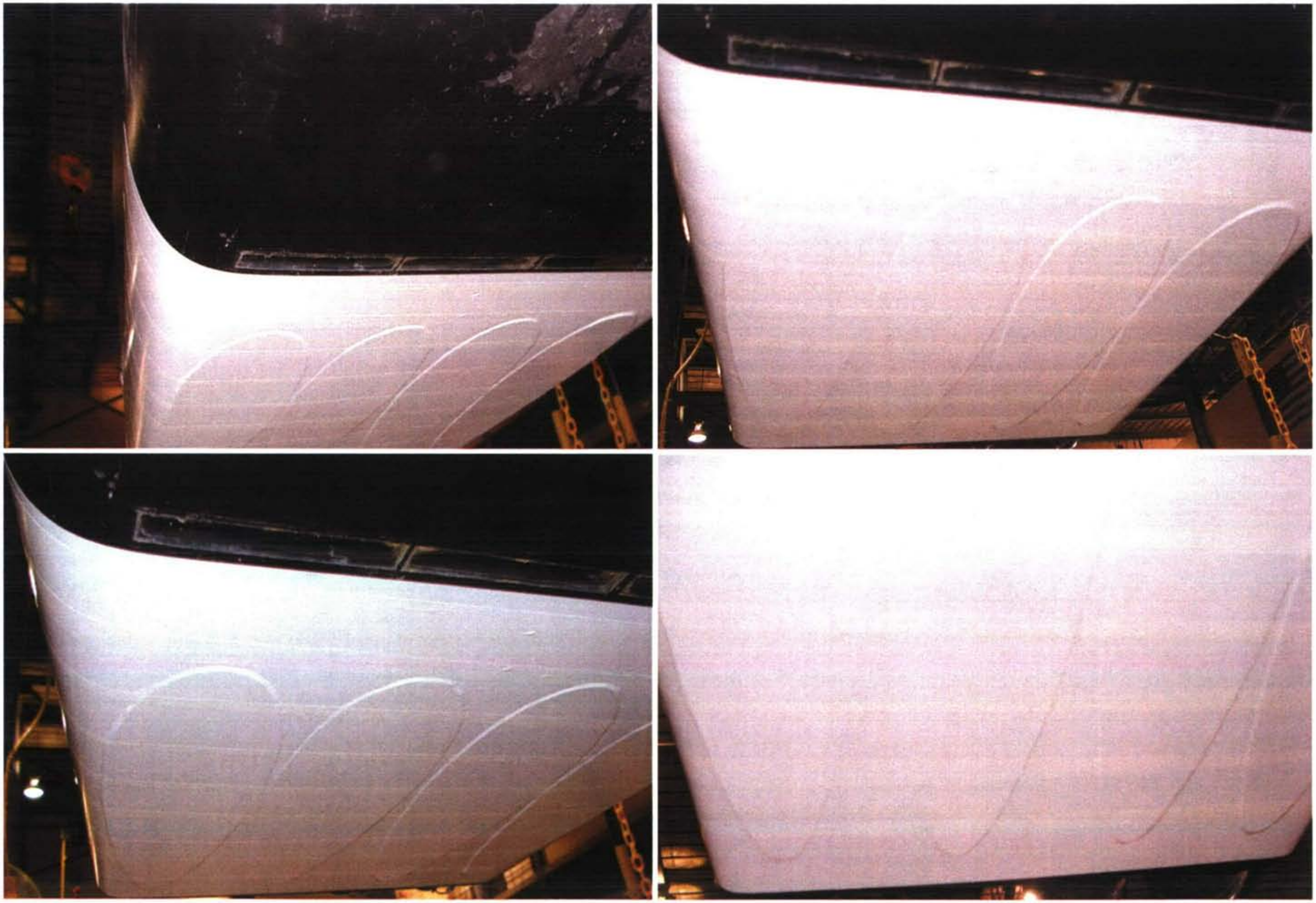

Fig B2. AxWJ Model 5662: Inlets covered for Bare Hull

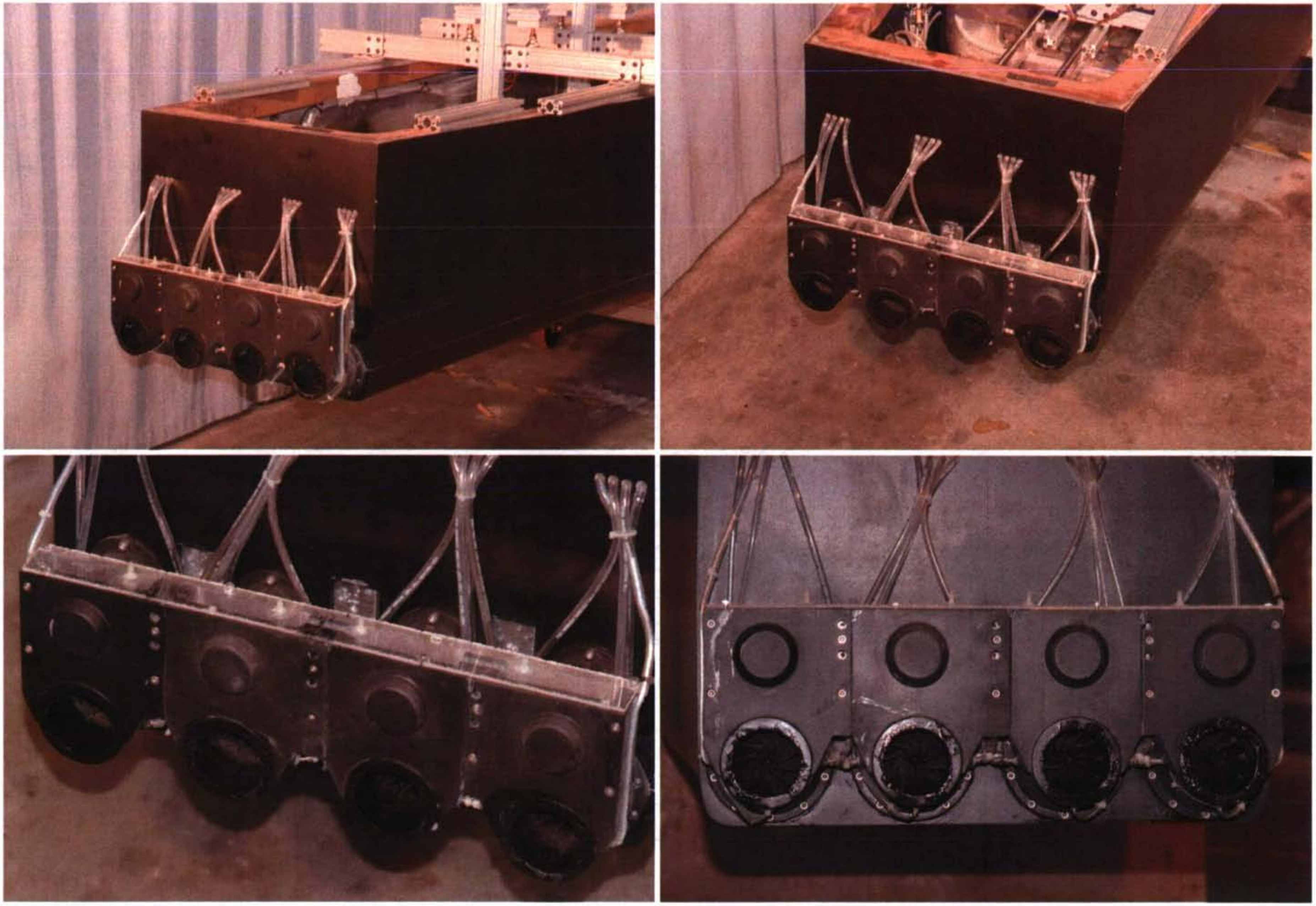

Fig B3. AxWJ Model 5662: LDV nozzles installed, inlets open

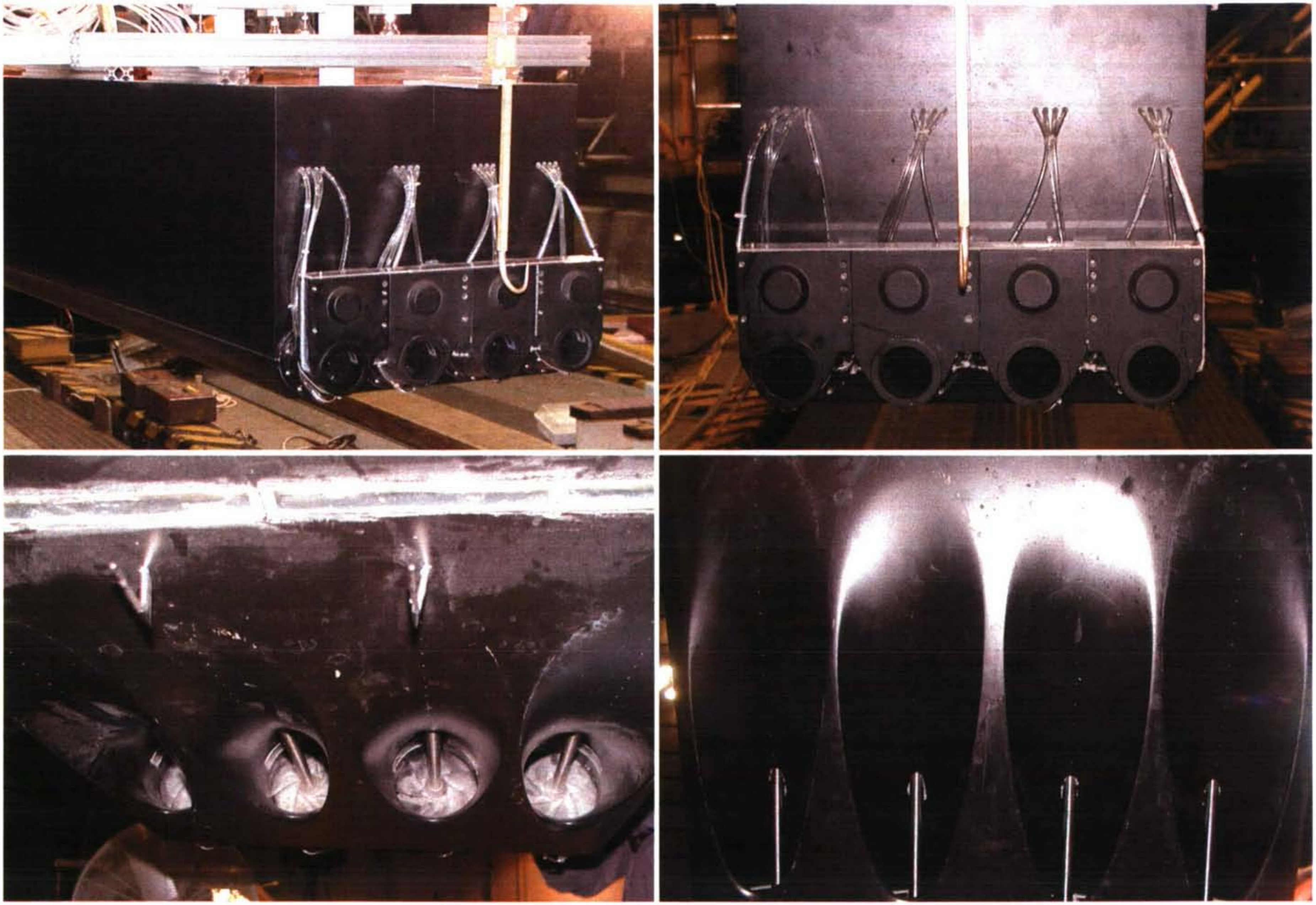

Fig B3. AxWJ Model 5662: LDV nozzles installed, inlets open - continued

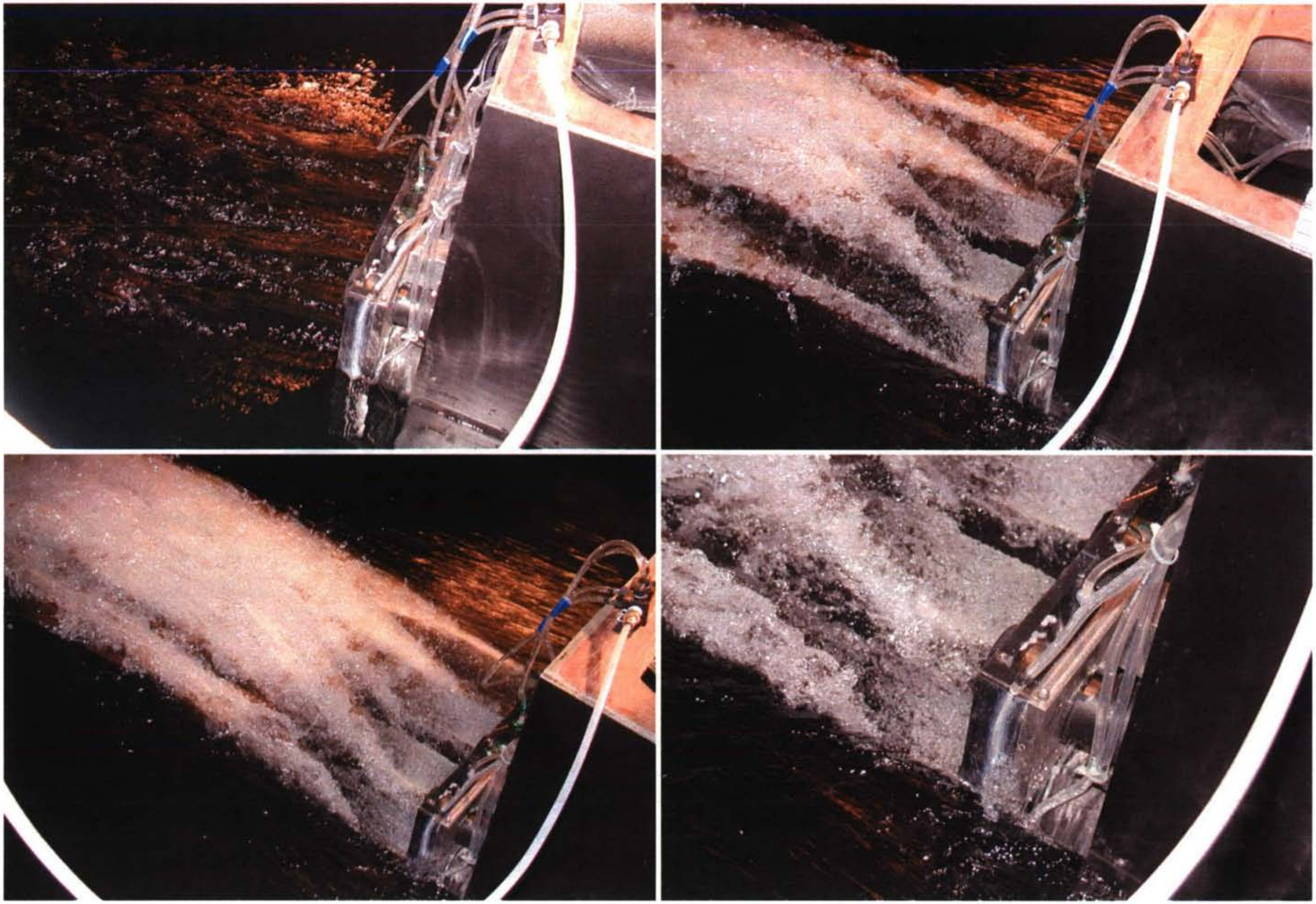

Fig B4. AxWJ Model 5662: Powering tests underway with and without LDV system operating (speeds unrecorded)

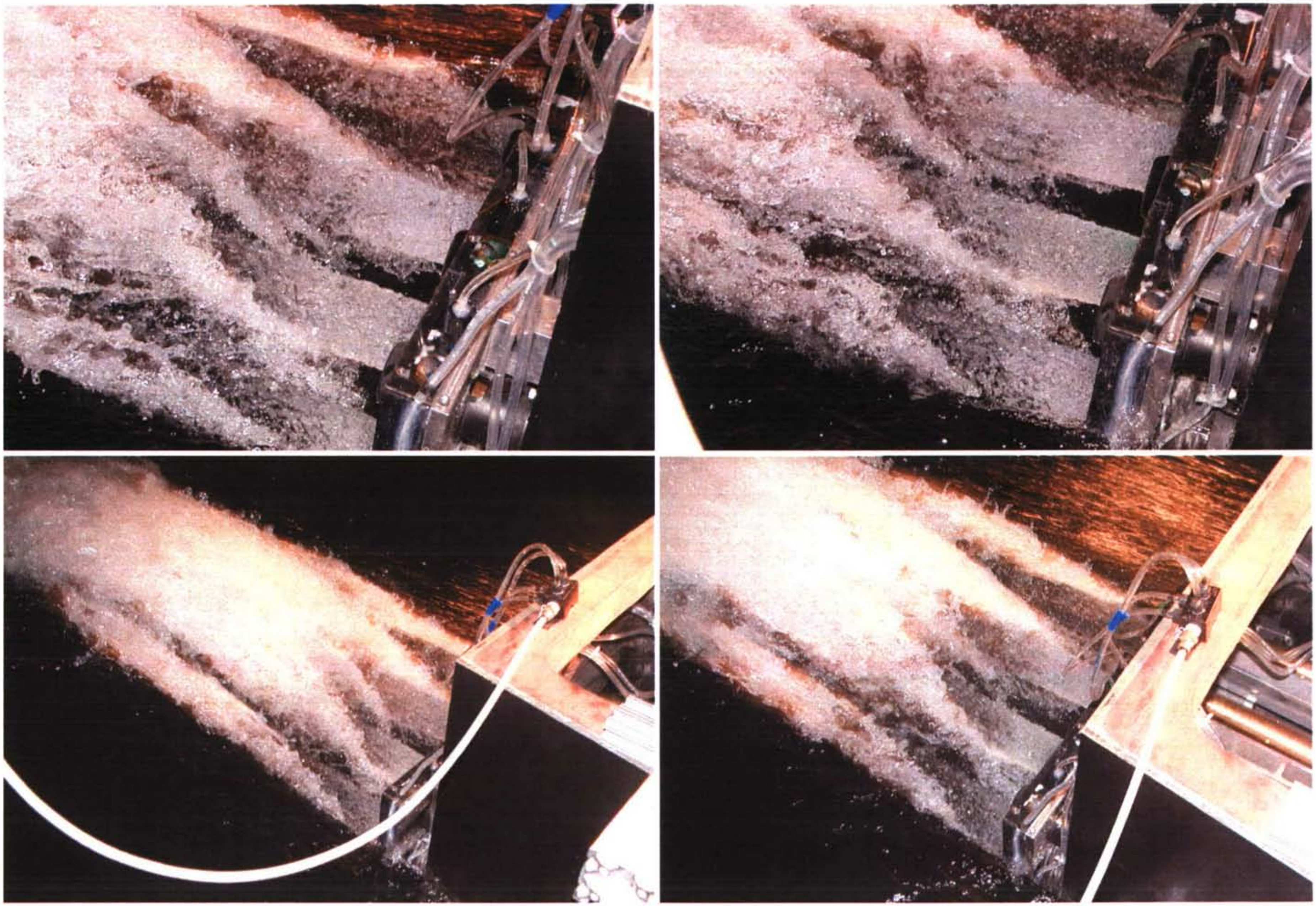

Fig B4. AxWJ Model 5662: Powering tests underway with and without LDV system operating (speeds unrecorded) - continued

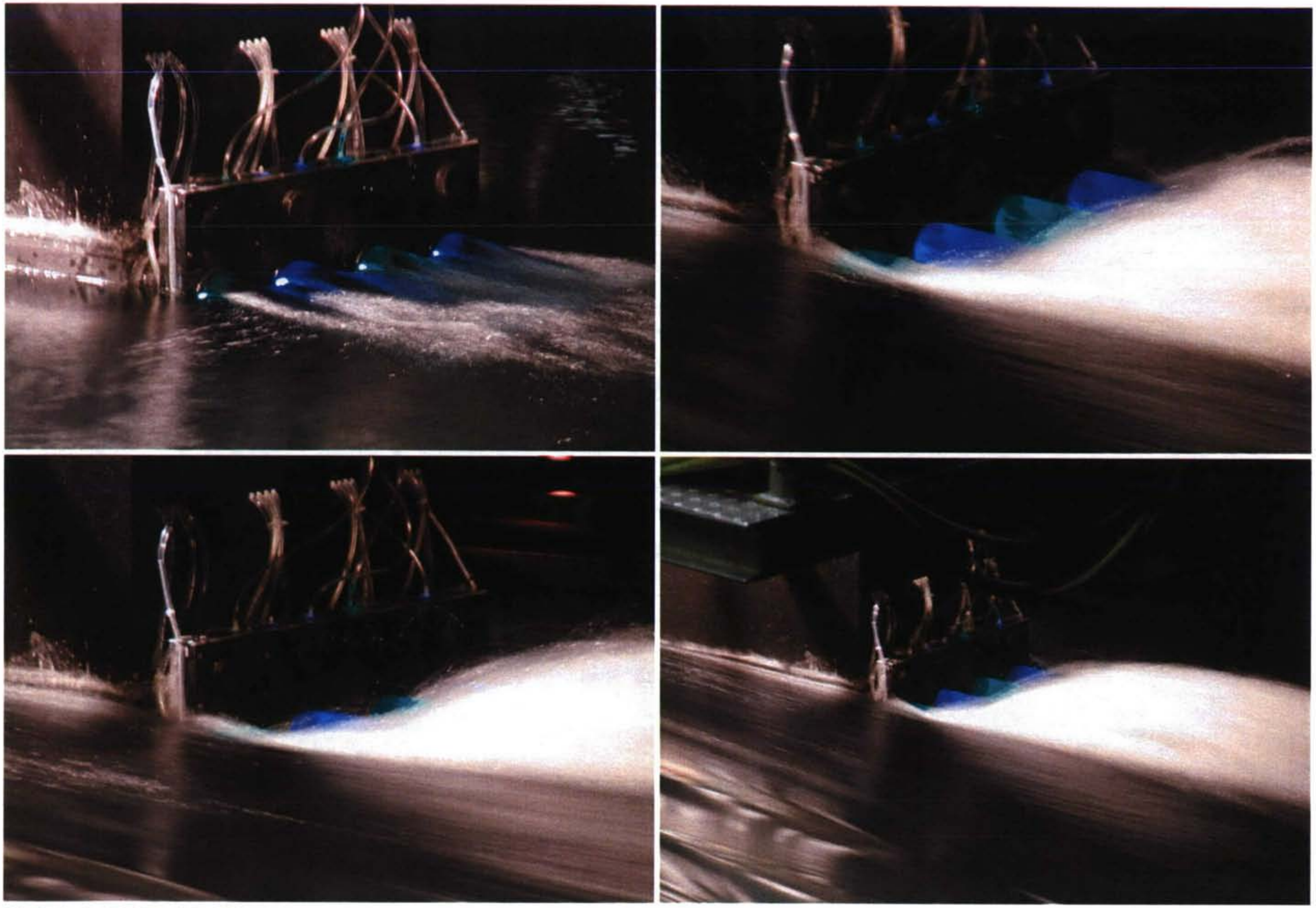

Fig B4. AxWJ Model 5662: Powering tests underway with and without LDV system operating (speeds unrecorded) – continued

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